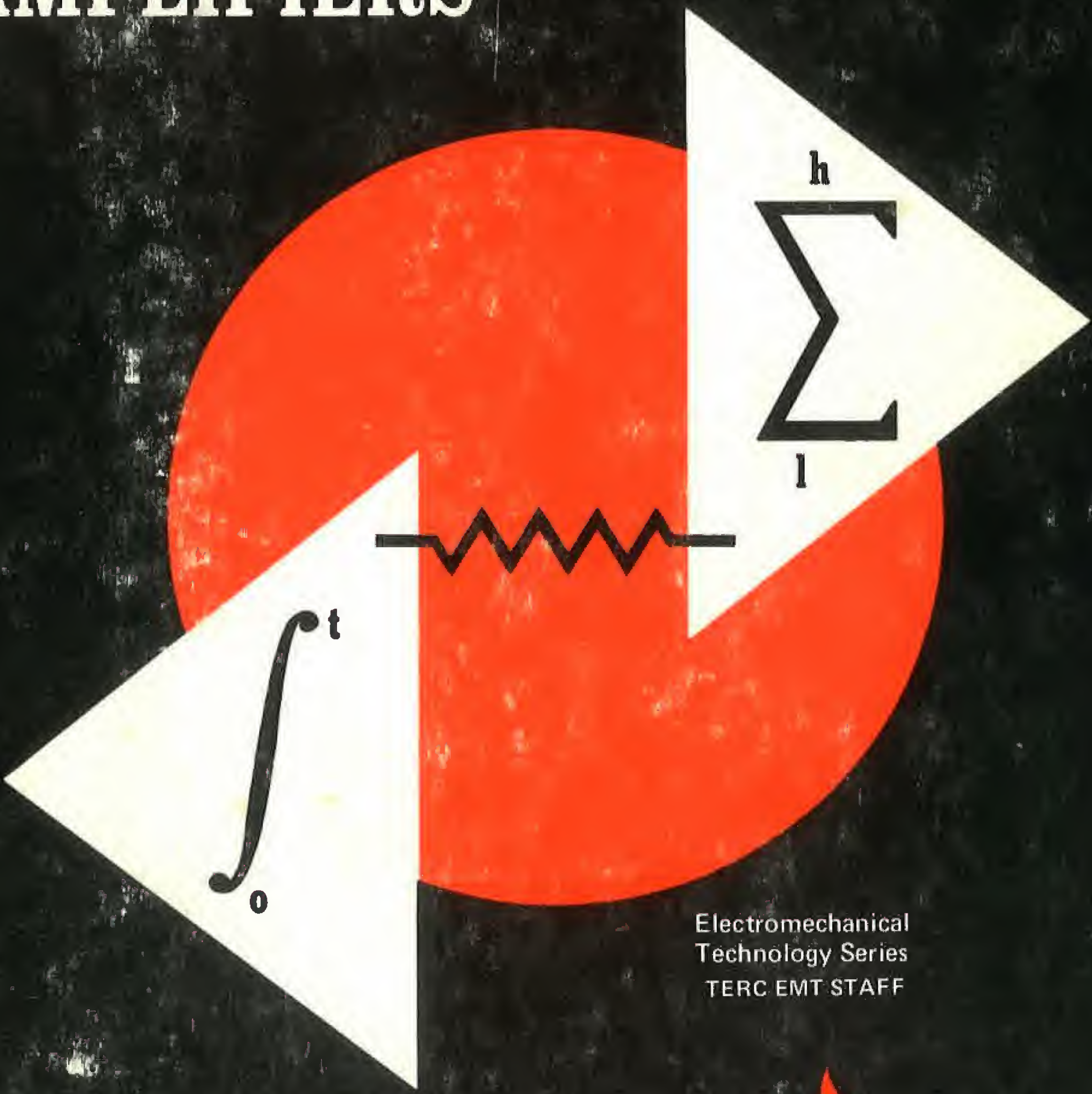
ELECTRONICS

AMPLIFIERS



Electromechanical Technology Series

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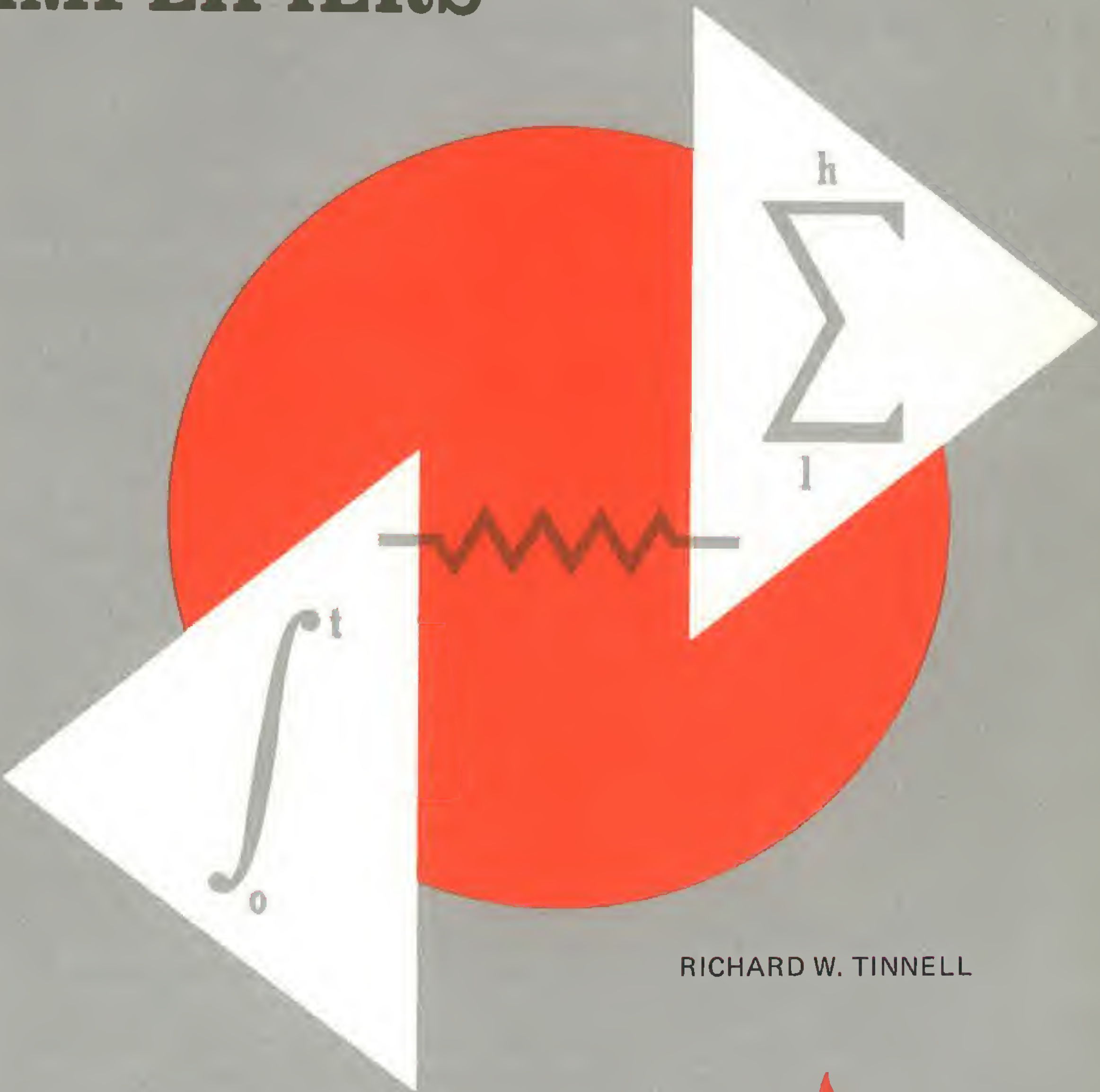

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Foreword

The marriage of electronics and technology is creating new demands for technical personnel in today's industries. New occupations have emerged with combination skill requirements well beyond the capability of many technical specialists. Increasingly, technicians who work with systems and devices of many kinds – mechanical, hydraulic, pneumatic, thermal, and optical – must be competent also in electronics. This need for combination skills is especially significant for the youngster who is preparing for a career in industrial technology.

This manual is one of a series of closely related publications designed for students who want the broadest possible introduction to technical occupations. The most effective use of these manuals is as combination textbook-laboratory guides for a full-time, post-secondary school study program that provides parallel and concurrent courses in electronics, mechanics, physics, mathematics, technical writing, and electromechanical applications.

A unique feature of the manuals in this series is the close correlation of technical laboratory study with mathematics and physics concepts. Each topic is studied by use of practical examples using modern industrial applications. The reinforcement obtained from multiple applications of the concepts has been shown to be extremely effective, especially for students with widely diverse educational backgrounds. Experience has shown that typical junior college or technical school students can make satisfactory progress in a well-coordinated program using these manuals as the primary instructional material.

School administrators will be interested in the potential of these manuals to support a common first-year core of studies for two-year programs in such fields as: instrumentation, automation, mechanical design, or quality assurance. This form of *technical core* program has the advantage of reducing instructional costs without the corresponding decrease in holding power so frequently found in general core programs.

This manual, along with the others in the series, is the result of six years of research and development by the *Technical Education Research Centers, Inc.,* (TERC), a national nonprofit, public service corporation with headquarters in Cambridge, Massachusetts. It has undergone a number of revisions as a direct result of experience gained with students in technical schools and community colleges throughout the country.

Maurice W. Roney

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Preface

Technology by its very nature is a laboratory-oriented activity. As such, the laboratory portion of any technology program is vitally important. This instructional material is intended to provide meaningful experience in electronic amplifier analysis for students of modern technology.

The topics included provide exposure to: basic principles of solidstate devices, amplifier circuits and applications.

The sequence of presentation chosen is by no means inflexible. It is expected that individual instructors may choose to use the materials in other than the given sequence.

The particular topics chosen for inclusion in this volume were selected primarily for convenience and economy of materials. Some instructors may wish to omit some of the exercises or to supplement of them to better meet their local needs.

The materials are presented in an action-oriented format combining many of the features normally found in a textbook with those usually associated with a laboratory manual. Each experiment contains:

1. An INTRODUCTION which identifies the topic to be examined and often includes a rationale for doing the exercise.
2. A DISCUSSION which presents the background, theory, or techniques needed to carry out the exercise.
3. A MATERIALS list which identifies all of the items needed in the laboratory experiment. (Items usually supplied by the student such as pencil and paper are normally not included in the lists.)
4. A PROCEDURE which presents step-by-step instructions for performing the experiment. In most instances the measurements are done before calculations so that all of the students can at least finish making the measurements before the laboratory period ends.
5. An ANALYSIS GUIDE which offers suggestions as to how the student might approach interpretation of the data in order to draw conclusions from it.
6. PROBLEMS are included for the purpose of reviewing the reinforcing the points covered in the exercise. The problems may be of the numerical solution type or simply questions about the exercise.

Laboratory report writing forms an important part of the learning process employed in this manual. Consequently, students should be encouraged to write at least a brief report for each exercise performed.

Students should be encouraged to study the test material, perform the experiment, work the review problems, and submit a technical report on each topic. Following this pattern, the student can acquire an understanding of, and skill with, basic amplifier circuits that will be extremely valuable on the job. For best results, these students should be concurrently enrolled in a course in technical mathematics (Introductory Calculus).

This material on basic amplifiers comprises one of a series of volumes prepared for technical students by the TERC EMT staff at Oklahoma State University, under the direction of D.S. Phillips and R.W. Tinnell. The principal author of this particular material was R.W. Tinnell.

An *Instructor's Data Book* is available for use with this volume. Mr. Kenneth F. Cathey was responsible for testing the materials and compiling the instructor's data book for them. Other members of the TERC staff madevvaluable contributions in the form of criticisms, corrections, and suggestions.

It is sincerely hoped that this volume as well as the other volumes in this series, the instructor's data books, and the other supplementary materials will make the study of technology interesting and rewarding for both students and teachers.

THE TERC EMT STAFF

TO THE STUDENT

Duplicate data sheets for each experiment are provided in the back of the book. These are perforated to be removed and completed while performing each experiment. They may then be submitted with the experiment analysis for your instructor's examination.

Contents

experiment 1 *DIODE CHARACTERISTICS*

INTRODUCTION. The simplest electronic device in common use is the diode. In this experiment we shall examine the basic terminal characteristics of three common types of diodes.

DISCUSSION. The essential characteristic of an electronic diode is the fact that it has different characteristics when electrons flow in different directions. As far as electrical terminal characteristics are concerned, the diode conducts more readily in one direction than in the other. In this experiment we shall consider the characteristics of only three types of diodes: the P-N junction diode, the avalanche breakdown diode, and the thermionic high vacuum diode.

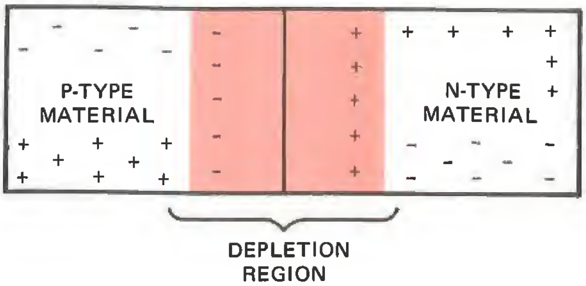


Fig. 1-1 A P-N Junction of Semiconductor Material

The conductive properties of so-called "pure" semiconductors, such as germanium and silicon, lay between those of the highly conductive materials (silver, copper, etc.) and the insulating materials (mica, quartz, etc.).

In order to produce useful semiconductor devices, small, carefully controlled amounts of impurities are added to silicon or germanium to produce "doped" semiconductors. If the impurity (called a donor) had more valence electrons compared to the base material, then the doped semiconductor is said to be of the *N-type* (N for the negative imbalance in valence electrons). Conversely, if the impurity (called an acceptor) has fewer valence electrons than the base semiconductor, then the combination is called a *P-type* material (P because of the positive imbalance in valence electrons). Both P- and N-type semiconductor materials are electrically neutral.

If pieces of N-type and P-type semiconductor material are joined together, as indicated in figure 1-1, then we have a *P-N junction*. When the two materials are joined, the acceptor and donor atoms in the region near the junction tend to offset each other's effect creating a region called the *depletion region,* because of the relative absence of mobile charge carriers (electrons or atoms with incomplete valence bands called "holes"). This process can perhaps be better understood by observing that there will be more electrons in the N material than in the P material because of the doping process. Similarly, there will be more holes in the P-type material than in the N-type. Conduction electrons in the N-type material will drift toward the junction as will holes in the P-type material. In the region of the junction, the two types of charge carriers will have a balancing effect, thereby creating the depleted region.

With the depletion region established, we see that the P-type material near the junction is depleted of holes and, therefore, appears to be negatively charged, while the N-type material is depleted of electrons and, hence, appears positively charged. The barrier (or junction) potential created in this manner is nor-

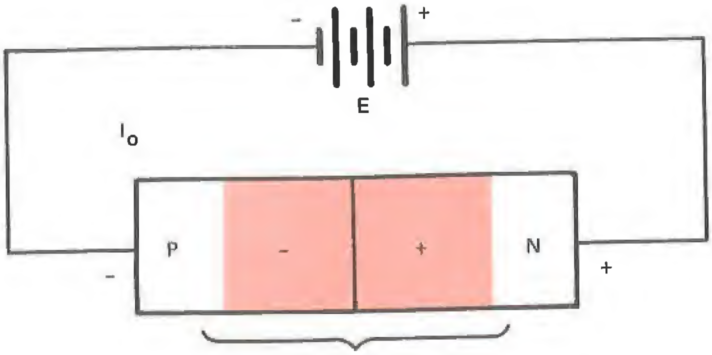


Fig. 1-2 A Reverse Biased P-N Junction

mally about 0.3 volts for a germanium device and depends on the amount of doping and on the temperature of the device.

If we apply a potential across the device, as described above, the result will be as indicated in figure 1-2. Note the direction in which the battery is connected, relative to P and N ends of the device. With the battery connected as shown, any conduction electrons in the P-type material and any holes in the N-type material will flow toward the junction, expanding the depletion region until the barrier potential across the junction is very near that of the battery. The net circuit current will therefore be very small (usually about 10 μA in a typical diode) and relatively constant. This condition is called *reverse biasing* the diode, and the small circuit current (I_o) is called the reverse or leakage current.

If we now reverse the battery, as shown in figure 1-3 (note the battery direction), electrons in the P-type material and holes in the N-type material are drawn away from the junction, thereby reducing the barrier potential and allowing a substantial amount of current to flow across the junction. This condition is termed *forward biasing.* The diode current will be

$$\boxed{I = I_o(\epsilon^{39E} - 1)} \qquad \textbf{(1.1)}$$

(assuming the diode temperature to be 20°C). This equation is reasonably accurate for either forward or reverse bias provided that E is

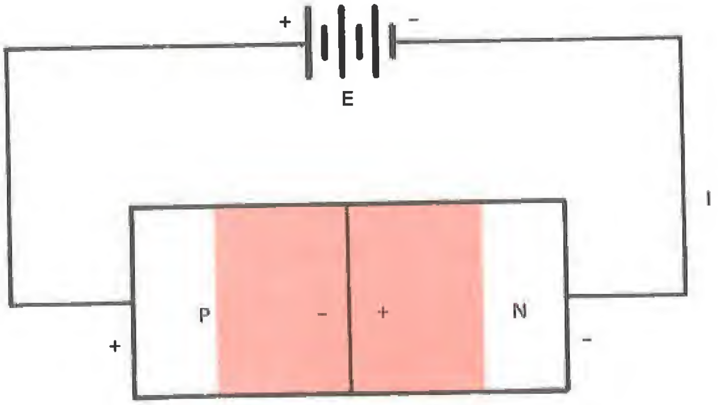


Fig. 1-3 A Forward Biased P-N Junction

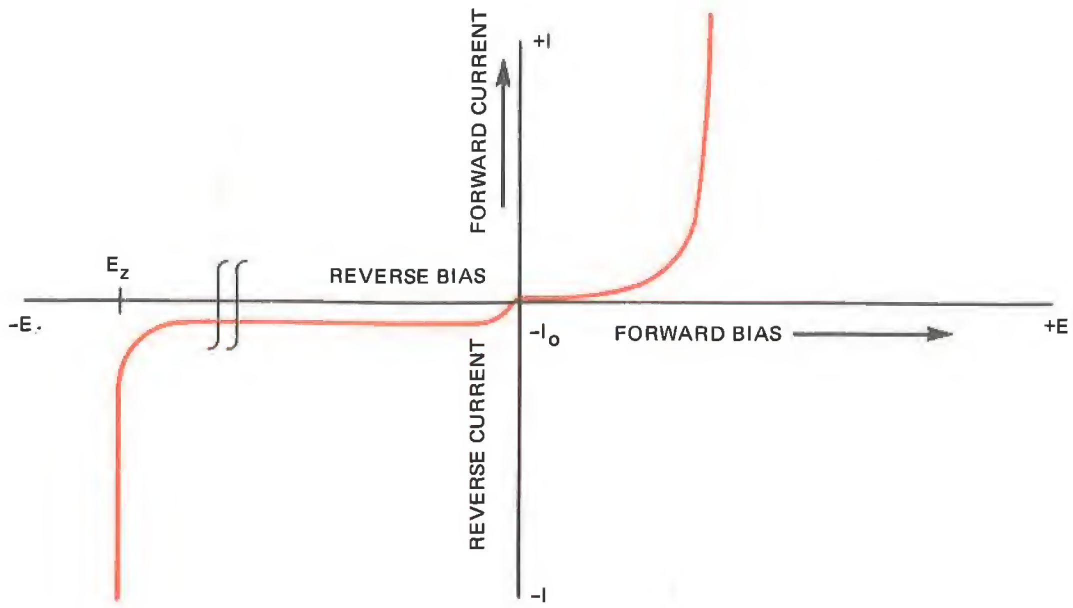


Fig. 1-4 A Diode Volt-Ampere Characteristic

taken to be positive for forward bias and negative for reverse bias.

A sketch of the plot of equation 1.1 is shown in figure 1-4. It should be observed at this point that if the reverse bias is increased sufficiently, the diode will break down. Similarly, if forward bias is increased sufficiently, the diode junction can be destroyed by excessive forward current.

Returning to figure 1-2, if we increase the reverse bias to a relatively high value, electrons in the P-type material (and holes in the N-type material) will be accelerated to high velocities as they move toward the junction. Under such conditions, it is possible to knock valence electrons loose from their parent atoms and force them into conduction. This process tends to avalanche as one carrier knocks several others into conduction and they in turn knock even more carriers into conduction. This phenomenon or other similar ones is called avalanche or *zener* breakdown and diodes themselves are called *zener diodes.*

The reverse bias voltage at which zener diodes break down is called the *zener voltage* of the diode and its value can be controlled in manufacture. The useful characteristic of a zener diode is that after breakdown is achieved, the voltage (E_Z) across the diode is constant and independent of the current flow. It is possible to destroy a zener diode by excessive power dissipation, but otherwise the breakdown process does not damage it.

It should be noted at this point that equation 1.1 is not valid when the diode is operating in breakdown mode. For practical purposes, the diode current after breakdown is determined exclusively by the resistance effectively in series with the diode.

Figure 1-5 shows the schematic symbols used to represent the P-N junction diode, the

Fig. 1-5 Schematic Symbols for Various Diodes

zener diode, and the thermionic high vacuum diode discussed below. The letter symbols are included only for clarification and do not usually appear with the symbols.

The first thermionic high vacuum diode was built about 1884 by Thomas Edison in conjunction with the development of the incandescent lamp. It was J.A. Fleming, however, who developed the diode as a device unto itself and patented it in 1905.

The thermionic high vacuum diode is composed of an evacuated envelope (usually of glass) which contains a *cathode* capable of emitting electrons when heated; a *filament* to heat the cathode, and an anode (or *plate*) to collect the emitted electrons.

The operation of a vacuum diode can perhaps best be understood by considering the cathode action with *no potential* applied to the plate. Let us presume that the *filament* is being supplied with its rated power and is heating the cathode. The cathode is coated with a *thermoemissive* material such as barium or strontium oxide. As the cathode heats up, this coating emits electrons into the evacuated space around the cathode structure. As a result of these emitted electrons, the space in the region of the cathode becomes charged negatively. This process continues until the *space charge* is sufficiently great that it repels any additional emitted electrons back into the cathode surface coating. At this point the space charge is said to be at thermal equilibrium.

If we now apply a voltage to the *non-emissive* plate electrode (iron or nickel), with the polarity shown in figure 1-6(a), the negative potential on the plate tends to repel the space charge electrons and force them closer to the cathode. Since the plate is non-emissive, no current flows through the diode. We therefore consider a negative plate potential (with respect to the cathode) to be a reverse bias.

On the other hand, if the battery is reversed, as shown in figure 1-6(b), then the positive plate potential attracts the space charge electrons and current flows in the diode. Figure 1-6(b) is therefore the forward-biased condition.

As the plate electrode becomes more and more positive, greater numbers of space-charged electrons are drawn to it. As electrons flow out of the space charge toward the plate, the cathode emits more electrons in an attempt to restore thermal equilibrium. When the point is finally reached where the cathode can no longer replace the electrons leaving the space charge, then the space charge becomes completely *neutralized* by the plate and electrons flow directly from the cathode to the plate as rapidly as they are emitted. Under this last condition we say that the diode is *saturated.* This condition rarely occurs in normal operation of a diode.

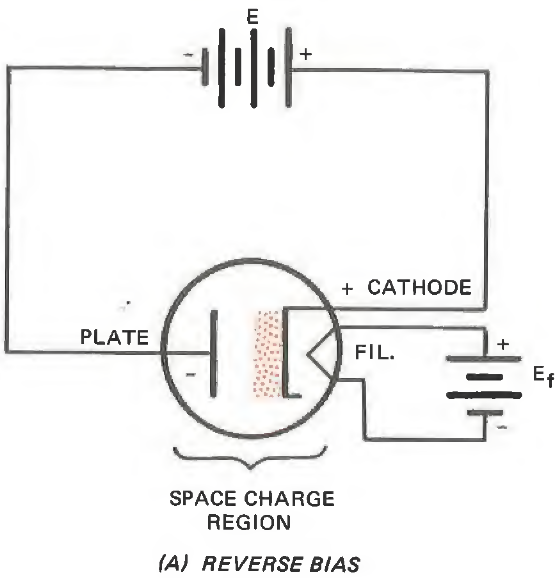


Fig. 1-6 Current Flow in a Vacuum Diode

Based on the above discussion, it should be apparent that the volt-ampere characteristic of a thermionic high vacuum diode is very much like that of a P-N junction.

Breakdown does occur in vacuum diodes when the negative plate potential is sufficiently high. However, this condition should be avoided as it physically damages the diode.

In the forward-biased direction, a diode has both a static and dynamic resistance just as any other nonlinear resistor does. Referring to the diode characteristic shown in figure 1-7, the static resistance at any point (P) may be determined by

$$R = \frac{E_1}{I_1} \tag{1.2}$$

The dynamic resistance, on the other hand, may be *approximated* at point P by

$$\boxed{r \approx \frac{\Delta E}{\Delta I}} \tag{1.3}$$

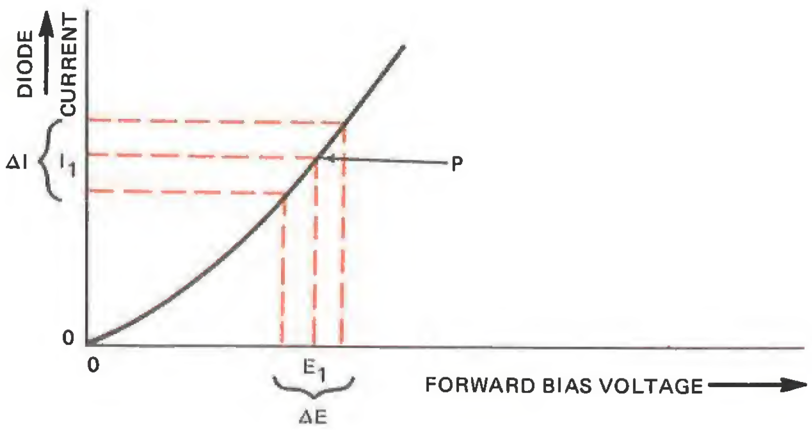


Fig. 1-7 Determination of Static and Dynamic Resistance

In the case of solid-state (semiconductor) diodes, the values are referred to as the static and dynamic *forward resistance* and the symbols R_D and r_D are frequently used. For a vacuum diode the two values are called the static and dynamic *plate resistance* (R_p and r_p). In most cases the vacuum diode resistances will be from 200 to 2000 ohms while solid-state diodes tend to be more like 2 to 200 ohms.

MATERIALS

- 1 Variable DC power supply (0 - 40V)
- 2 VOM (volt-ohm meters) or FEM (field effect meters)
- 1 220-ohm resistor
- 1 Silicon diode type 1N914 or equivalent
- 1 Zener diode type 1N3018B or equivalent
- 1 Vacuum diode type 6AX5GT or equivalent
- 1 6.3V filament power supply
- 1 Octal tube socket with mounting board

PROCEDURE

1. Using the silicon diode, assemble the circuit shown in figure 1-8.

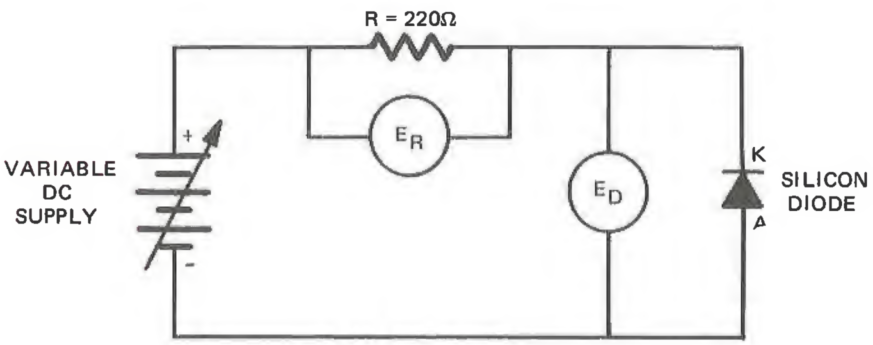


Fig. 1-8 The First Experimental Circuit

2. Starting at zero volts, adjust the variable DC supply in 1/2-volt increments and record the voltage across the 220-ohm resistor. (*See Fig. 1-10, Data Tables, pages 8-11.*)
3. Also record the circuit current ($I_D = E_R/R$) and the diode voltage E_D.
4. Return the variable DC supply to zero and reverse the diode in the circuit.
5. Repeat steps 2 and 3.
6. Replace the silicon diode with the zener diode and repeat steps 2 through 5.
7. Connect the circuit shown in figure 1-9.
8. Repeat steps 2 through 5.
9. On a single sheet of graph paper, plot the silicon diode volt-ampere characteristic using your measured data.
10. On the same sheet of graph paper, plot equation 1.1.

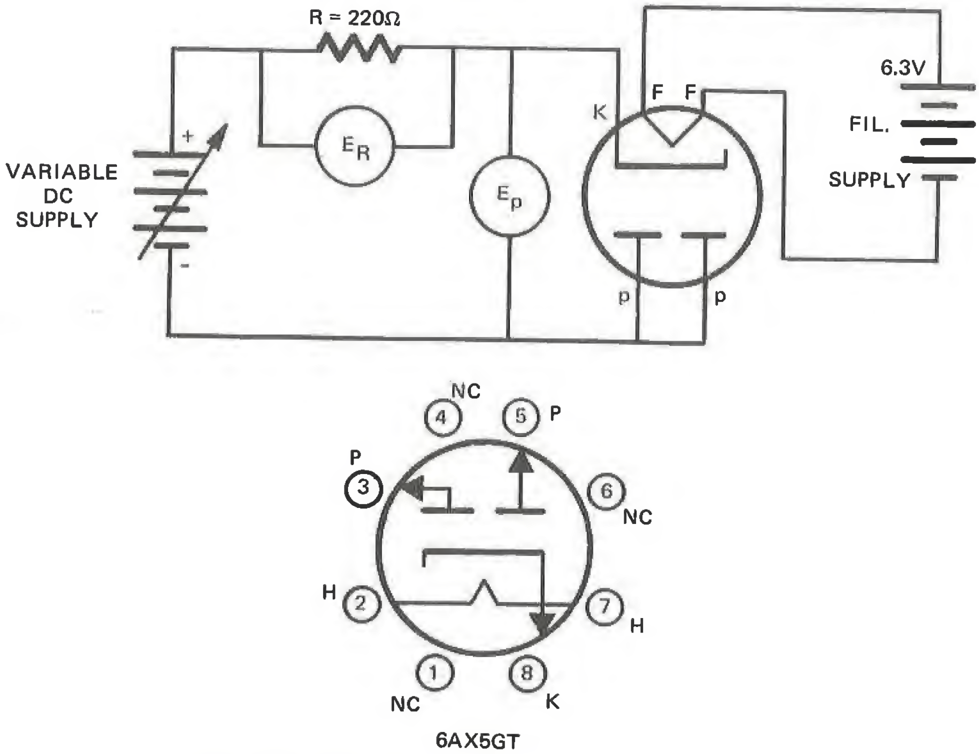


Fig. 1-9 The Second Experimental Circuit

11. On a second sheet of graph paper, plot the volt-ampere characteristic of all three diodes on a single set of axes.

ANALYSIS GUIDE. In analyzing these data you should compare the silicon diode characteristic to the plot of equation 1.1. Similarly, compare the characteristic curve of each diode to the other two. Discuss any similarities and differences between the curves.

PROBLEMS

1. Compute the static and dynamic resistance of each diode at the points where the diode current is 20, 40, 60, 80, and 100 mA.
2. On a third sheet of graph paper plot curves of the static and dynamic resistance (on the vertical axis) versus current (on the horizontal axis).
3. Write a brief comparison of the resistance characteristics of the three diodes.
4. Plot the silicon diode curve on a sheet of similog graph paper. Why does it look different from the plot on linear paper?
5. Describe in your own words how a semiconductor diode works.
6. Repeat problem 5 for a vacuum diode.

Silicon Diode
Reverse Biased

E_R	E_D	I_D

Silicon Diode
Forward Biased

E_R	E_D	I_D

Fig. 1-10 The Data Tables

Zener Diode
Reverse Biased

E_R	E_D	I_D

Zener Diode
Forward Biased

E_R	E_D	I_D

Fig. 1-10 The Data Tables (Cont'd)

Vacuum Diode
Reverse Biased

E_R	E_p	I_p

Vacuum Diode
Forward Biased

E_R	E_p	I_p

Fig. 1-10 The Data Tables (Cont'd)

Silicon Diode Resistance

I_D (mA)	R_D	r_D
20		
40		
60		
80		
100		

Zener Diode Resistance

I_D (mA)	R_D	r_D
20		
40		
60		
80		
100		

Vacuum Diode Resistance

I_p (mA)	R_p	r_P
20		
40		

Fig. 1-10 The Data Tables (Cont'd)

experiment 2 HALF-WAVE POWER SUPPLIES

INTRODUCTION. Virtually all electronic circuits require some type of DC power supply. The two most common types of DC supplies are the battery pack (one or more batteries) and the AC rectifier. In this experiment we shall examine the operating principles of one kind of AC rectifier circuit.

DISCUSSION. In many cases a supply of alternating current is available at a location where an electronic circuit is to operate. The problem then becomes to convert the available AC to a direct current. Circuits used to perform this conversion are called *rectifier* circuits.

The most elementary rectifier circuit is the *halfwave diode rectifier* shown in figure 2-1. The diode (D_1) allows current (i) to flow in only one direction through the load resistor (R). During alternate half cycles, the diode is *back-biased* and no current can flow. As a result, current flows through the load only during one half of the input cycle, as seen in figure 2-2. If we assume that the diode is perfect, it has zero forward resistance and infinite back resistance, then the load current will be

$$i = \frac{e}{R} = \frac{E_m}{R} \sin \omega t$$

during the nonconducting half cycle.

The DC current that flows in the load is simply the average of the current taken over one complete cycle. This current can be found by determining the area under the load current curve for a complete cycle. If we do this we will find that

$$\boxed{I_{DC} = \frac{E_m}{\pi R}} \qquad (2.1)$$

And since the DC load voltage is

$$E_{DC} = I_{DC} R$$

we have

$$\boxed{E_{DC} = \frac{E_m}{\pi}} \qquad (2.2)$$

We should observe at this point that these quantities are only approximate because in reality we never have a completely perfect diode. In actual practice, the values of I_{DC} and E_{DC} will always be slightly less than that predicted by equations 2.1 and 2.2 respectively.

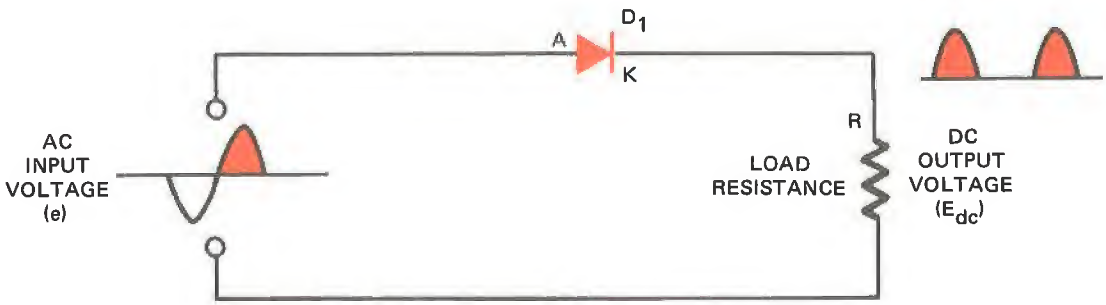


Fig. 2-1 A Basic Halfwave Rectifier

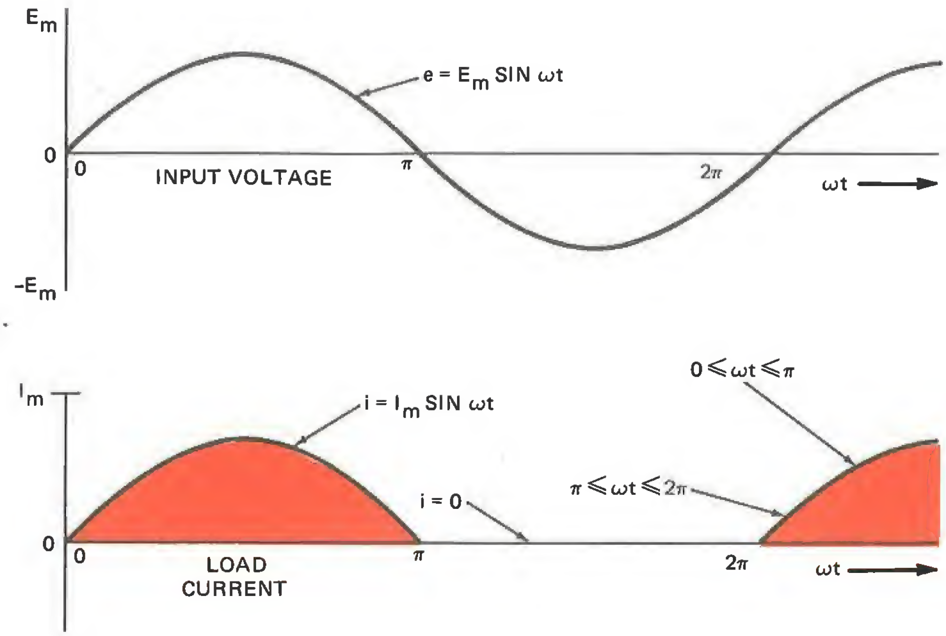


Fig. 2-2 Input Voltage and Load Current

As we see from the equations given above, the value of the DC voltage and current depends on the peak value of the AC input voltage. Consequently, it is common practice to use a *transformer* to establish the desired AC level. Figure 2-3 shows a halfwave rectifier operated from a 117-volt 60-Hz line and using a transformer input.

We would, of course, choose the transformer to have a turns ratio of

$$\frac{N_s}{N_p} = \frac{0.707\ E_m}{117}$$

where E_m is the desired peak secondary voltage.

As can be seen in figure 2-2, the DC voltage and current are by no means constant quantities. They occur in the form of 60-Hz pulses. In most practical circuits, such *pulsed* DC is not satisfactory. It is, therefore, usual practice to use a *filter* to convert the output to a more constant level.

The simplest type of filter is a single shunt capacitor, as shown in figure 2-4. When

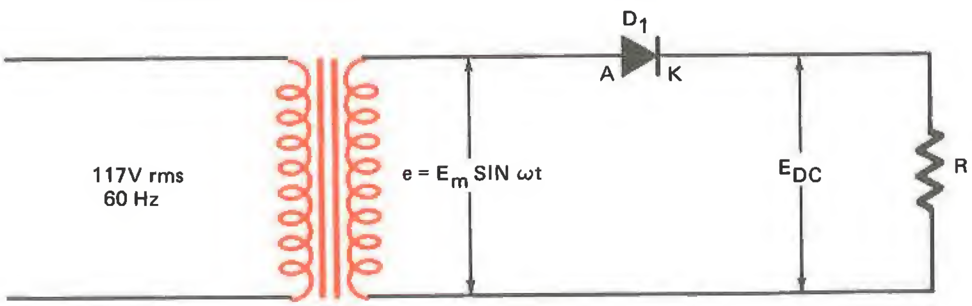


Fig. 2-3 A Halfwave Rectifier with Transformer Input

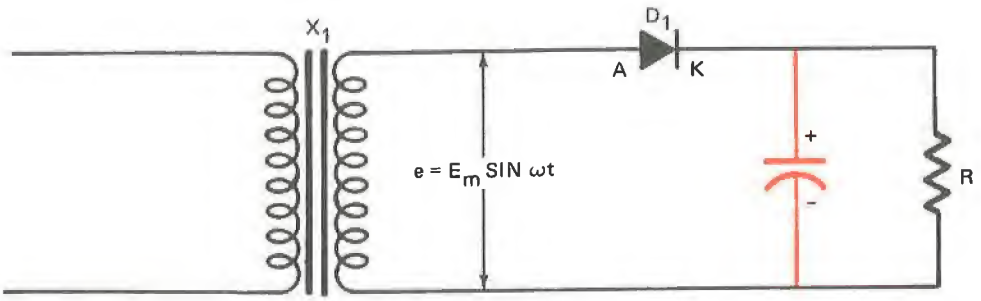


Fig. 2-4 A Halfwave Rectifier with Capacitor Filter

the diode is conducting, the capacitor charges to a potential approximately equal to E_m. When the voltage across the load decreases below the value of E_m, then the capacitor discharges through the load, thereby tending to hold the load voltage constant. Figure 2-5 shows voltage across the load (and the capacitor) compared to the input AC voltage. Notice that load voltage is now more nearly constant than it was without the *capacitor filter.*

The amount of drop in load voltage depends on the time constant of R and C. If the time constant is very long compared to the time of one input cycle, then the load voltage will be quite constant and equal to E_m. We can, of course, lengthen the time constant by making either R or C larger. In a practical case, however, R is usually more or less fixed; and the only alternative is to increase C to provide a long time constant.

Unfortunately, if we make C larger and larger, then we must provide more and more peak charging current. This peak charging current must flow through the diode, and we eventually reach a point at which the diode is damaged. As a result, the single capacitor filter is not frequently used in actual practice.

A much more practical filter is the *π network* shown in figure 2-6.

In this case, the filtering is accomplished in two steps, and the diode is protected against excessive charging current by the series resistors R_1 and R_2.

The voltage waveform across C_1 would be about the same as that shown in figure 2-5 (as load voltage) and the voltage across the load would be even smoother.

In some cases, the load current is high

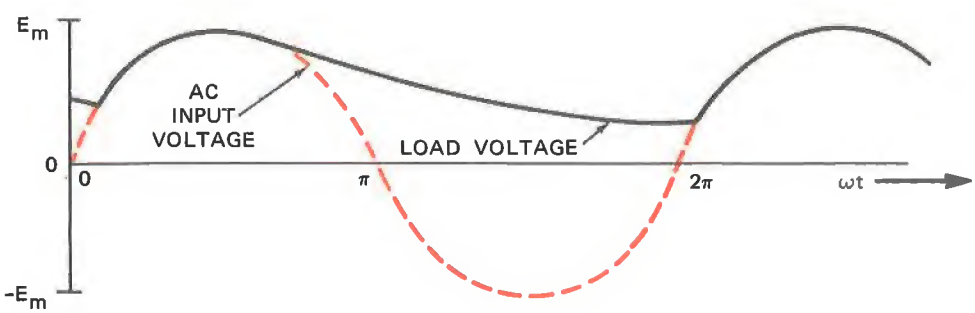


Fig. 2-5 Shunt Capacitor Filtering Action

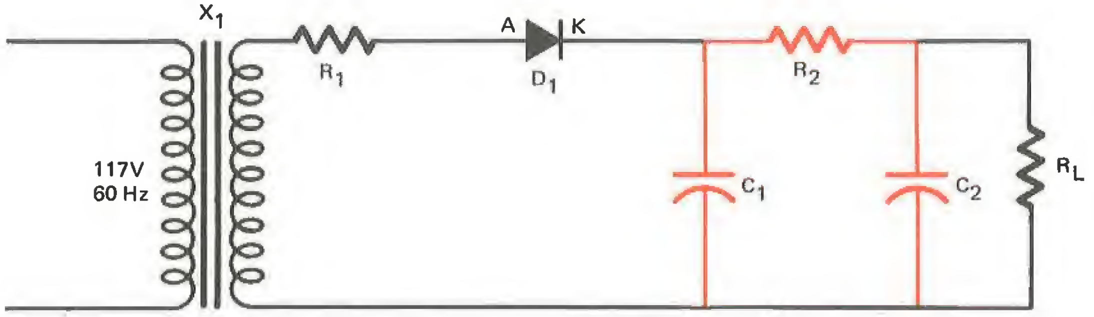


Fig. 2-6 Halfwave Rectifier with π Filter

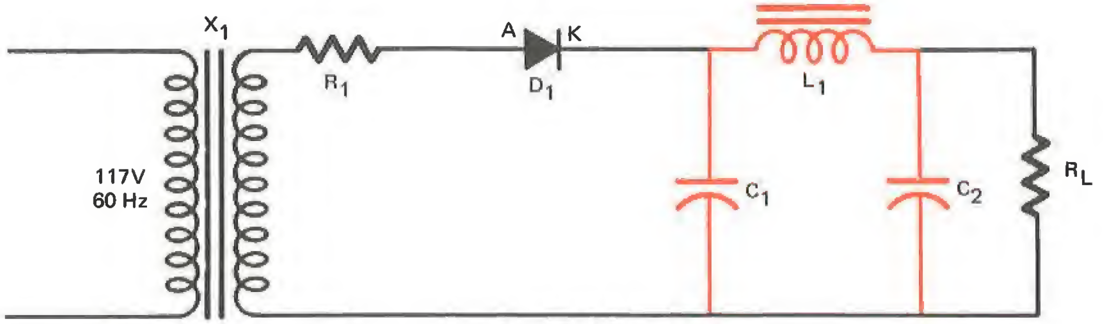


Fig. 2-7 Halfwave Rectifier with LC Filter

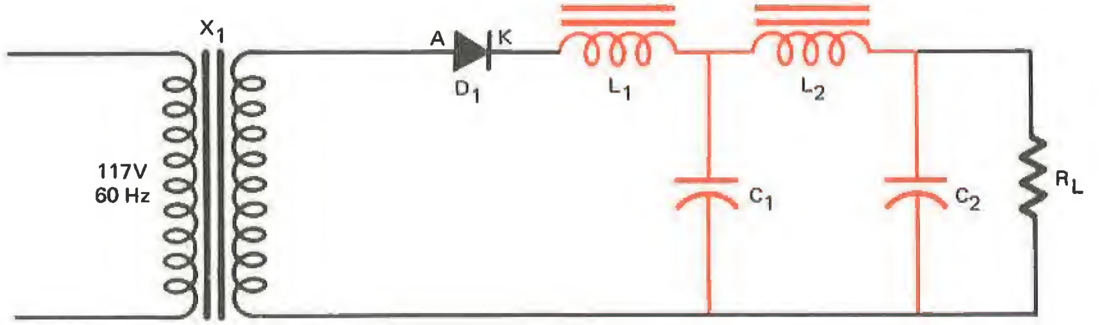


Fig. 2-8 Halfwave Rectifier with Two L-Section Filters

enough that the voltage drop across R_2 is *prohibitively* high. In such a case, R_2 may be replaced with an inductor called a *filter choke,* as in figure 2-7. The filter choke provides a high impedance for AC ripple while having a relatively low DC resistance. Such a filter, while being expensive, provides very good filtering action. When even finer filtering is required, a second choke may be included, as seen in figure 2-8. When this input filter choke (L_1) is included, it also provides overcurrent protection for the diode, making R_1 unnecessary. Each LC pair (L_1C_1 and L_2C_2) is called an *L-Section;* and in extreme cases, more than two sections may be used.

MATERIALS

1 Power transformer (110V - 220V CT)
1 Silicon diode, type 1N914 or equivalent
1 Substitution box (0 - 100 kΩ 2W)
1 220-ohm 2W resistor
2 10 μF, 600W VDC capacitors
1 FEM or VOM
1 Oscilloscope
1 Variable transformer (0 - 130V)
4 Sheets of linear graph paper

PROCEDURE

1. Assemble the circuit shown in figure 2-9. **Set the resistance box for MAXIMUM resistance.**

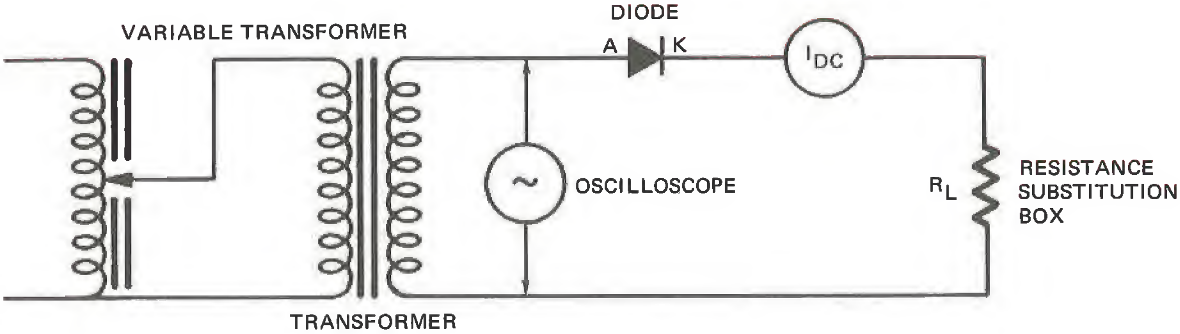


Fig. 2-9 The First Experimental Circuit

2. Set the input voltage for a transformer secondary voltage of 50V peak. Record the value of E_m in the data table, figure 2-10.
3. Set the resistance substitution box for a DC load current of about 5 mA. Record the value of R_L.
4. Make a sketch of the transformer secondary voltage waveform, then move the oscilloscope to the load and sketch the load voltage waveform. Indicate the amplitude and period of each part of the waveform.
5. Measure and record the value of the DC load voltage E_{DC}.
6. Using the appropriate equations from the discussion with the values of E_m and R_L, compute and record I_{DC} and E_{DC}.
7. Connect the 220-ohm resistor in series with the diode in the position occupied by the meter in figure 2-9. The voltage across this resistor is now directly proportional to the diode current. View the diode current waveform and sketch it. Indicate period and amplitude.
8. Connect one of the 10 μF capacitors across the load resistor and repeat steps 4, 5, and 7.
9. Add a second capacitor (making the total filter capacitance equal to 20 μF), and repeat steps 4, 5, and 7.

10. Move one of the capacitors to the other side of the 220-ohm resistor forming a π network filter.

11. View the waveforms across:

    (a) the transformer secondary
    (b) the input filter capacitor
    (c) the load resistance.

    Sketch each of these waveforms.

12. Measure and record the load voltage E_{DC} for each circuit.

Circuit Values With No Filter					10 μF Filter	20 μF Filter	π Filter
E_m	R_L	E_{DC} Meas	I_{DC} Comp	E_{DC} Comp	E_{DC} Meas	E_{DC} Meas	E_{DC} Meas

Fig. 2-10 The Data Table

ANALYSIS GUIDE. In analyzing the results of this experiment, you should be concerned about the accuracy with which the equations given in the discussion predicted the unfiltered output of the rectifier. Also consider the extent to which the discussion of filter action was confirmed by the results.

PROBLEMS

1. A certain halfwave rectifier has an input voltage of 168 sin 377t and a load of 10k ohms. What would be the approximate values of E_{DC} and I_{DC} if:

    a) the output were unfiltered?
    b) the output is filtered by a single 80 μF capacitor? (Assume E_{DC} = the peak AC voltage. The time constant is RC.)

2. What would be the effect on E_{DC} if the diode in problem 1 had:

    a) appreciable forward resistance?
    b) a back resistance of the same order of magnitude as R_L?

3. Draw circuit diagrams showing how a halfwave rectifier can be used to produce:

    a) a positive output voltage.
    b) a negative output voltage.
    c) both a positive and a negative output simultaneously.

INTRODUCTION. The full-wave electronic power supply is perhaps the most popular type of AC to DC converter. In this experiment we shall examine the operation of two basic *full-wave rectifier* circuits.

DISCUSSION. Let us consider the operation of the circuit shown in figure 3-1.

If we apply a 60-Hz sinusoidal voltage to the primary of the transformer, then the voltage across one-half of the secondary winding (e_1, for example) will be

$$e_1 = E_m \sin \omega t$$

Across the other half of the secondary winding we will have a similar voltage, e_2. The main difference between e_1 and e_2 will be that they are 180 degrees out of phase. Consequently, e_2 will be

$$e_2 = -e_1 = -E_m \sin \omega t$$

If we consider the diodes to be ideal (having zero forward resistance and infinite back resistance) and the instantaneous polarity across the secondary winding to be as shown in figure 3-1, then diode D_1 can conduct and D_2 cannot. On the alternate half of the input cycle, D_1 cannot conduct but D_2 can.

When current flows through D_1, the complete current path is from the upper half of the transformer secondary (e_1) through the common contact to the load, upward through the load to point A, then through D_1 and back to the transformer winding. Since no current flows through D_1 on the alternate half of the input cycle, the current waveform through D_1 will appear as shown in figure 3-2. The input AC waveform is also shown for purposes of comparison.

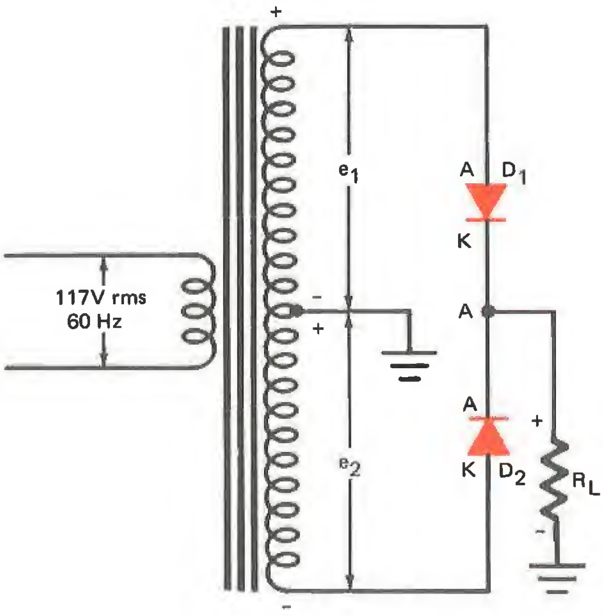


Fig. 3-1 A Basic Full-Wave Rectifier Circuit

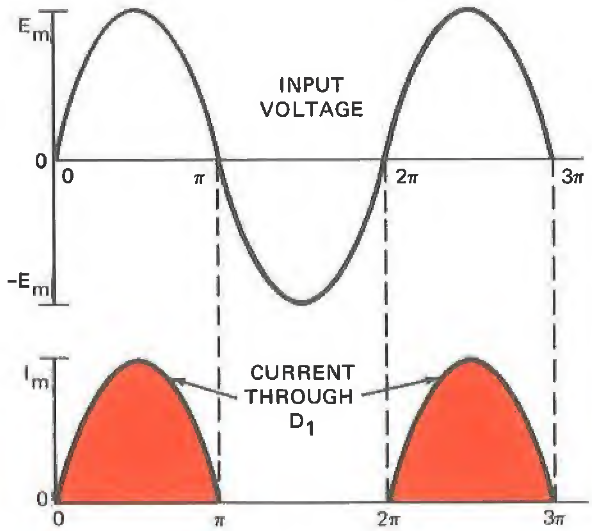


Fig. 3-2 The Current Through Diode D_1

On the alternate half of the input cycle, D_1 cannot conduct but D_2 can. During this half cycle, current flows from the lower half of the transformer secondary through the ground (common) system to the load, up through the load to point A, through D_2 and back to the transformer secondary. The current waveform through D_2 is shown with the input voltage in figure 3-3.

Since both diode currents flow through the load in the same direction, the load current waveform will be the combination of the diode currents, as shown in figure 3-4.

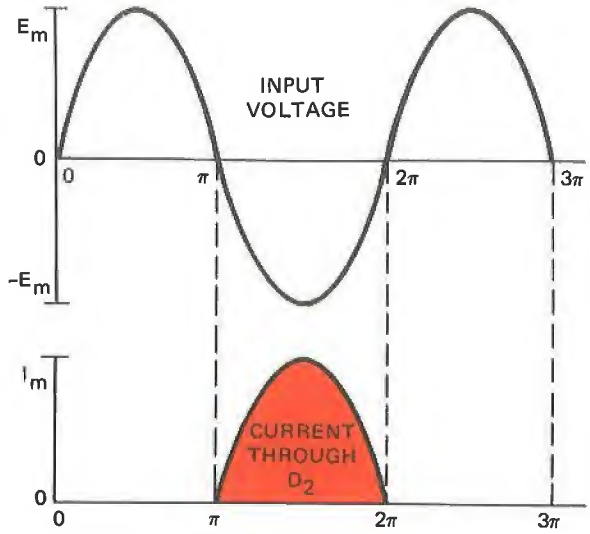


Fig. 3-3 The Current Through Diode D_2

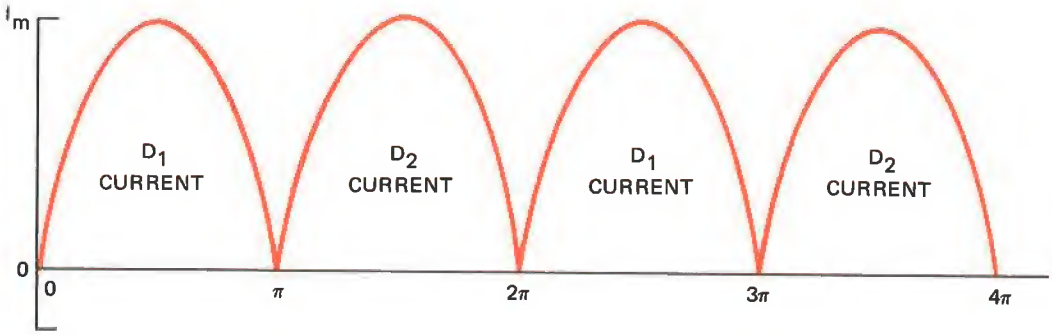


Fig. 3-4 The Load Current

Each of the half-cycle load current pulses will be sinusoidal (if the diodes are perfect), and we can find the average DC load current by using

$$\boxed{I_{DC} = \frac{2E_m}{\pi R_L}} \qquad (3.1)$$

Now since the DC load voltage is

$$E_{DC} = I_{DC}R_L$$

we see that

$$\boxed{E_{DC} = \frac{2E_m}{\pi}} \qquad (3.2)$$

In actual practice the diodes will not be all perfect; and as a result, the load voltage and current will be slightly less than the values predicted by equations 3.2 and 3.1, respectively.

As can be seen in figure 3-4, the DC voltage and current are by no means constant quantities. They occur in the form of 120-Hz pulses. In most practical circuits, such *pulsed*

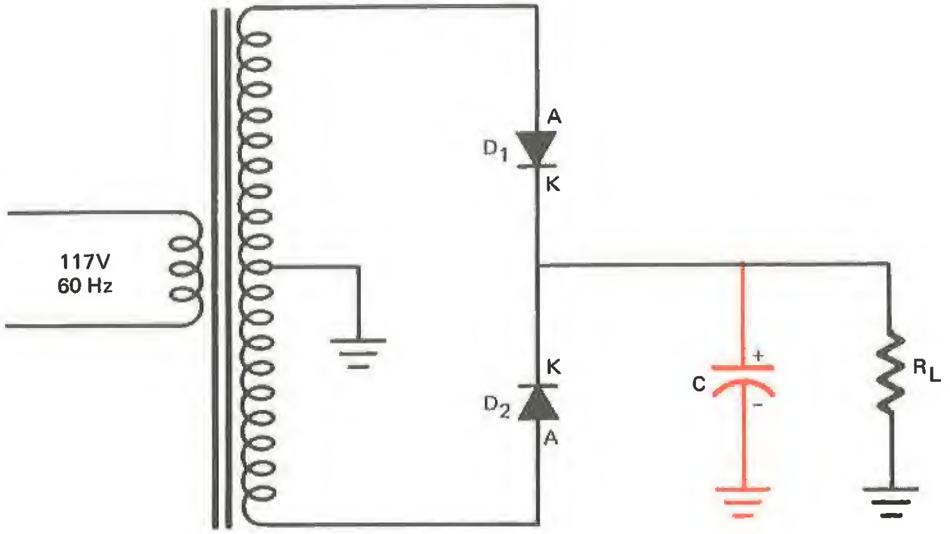


Fig. 3-5 Fullwave Rectifier with Shunt Capacitor Filter

DC is not satisfactory. It is, therefore, usual practice to use a smoothing filter to convert the output to a more constant level.

The simplest type of filter is a single *shunt* capacitor, as shown in figure 3-5. When a diode is conducting, the capacitor charges to a potential approximately equal to E_m. When the voltage across the load decreases below the value of E_m, then the capacitor discharges through the load, thereby tending to hold the load voltage constant. Figure 3-6 shows voltage across the load (and the capacitor) compared to the input AC voltage. Notice that load voltage is now more nearly constant than it was without the capacitor filter.

The amount of drop in load voltage depends on the time constant of R_L and C. If the time constant is very long compared to the time of one input cycle, then the load voltage will be quite constant and equal to E_m. We can, of course, lengthen the time

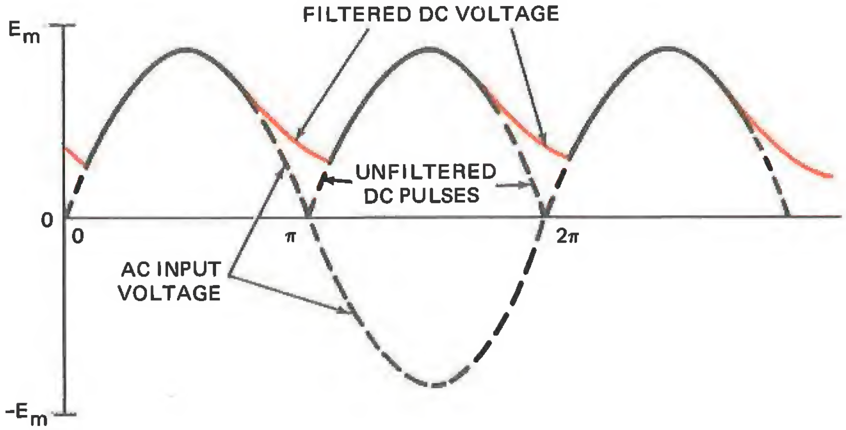


Fig. 3-6 Shunt Capacitor Filtering Action

constant by making either R or C larger. In a practical case, however, R is usually more or less fixed; and the only alternative is to increase C to provide a long time constant.

Unfortunately, if we make C larger and larger, then we must provide more and more peak-charging current. This peak-charging current must flow through the diodes, and we eventually reach a point at which the diodes may be damaged by excessive current. As a result, the single capacitor filter is not frequently used in actual practice.

A much more practical filter is the π network shown in figure 3-7. In this case, the filtering is accomplished in two steps, and the diodes are protected against excessive charging current by the series resistor, R_1.

The voltage waveform across C_1 would be about the same as that shown in figure 3-6 (as the load voltage), and the voltage across the load would be smoother.

In some cases, the load current is high enough that the voltage drop across R_1 is prohibitively high. In such a case, R_1 may be replaced with an inductor called a *filter choke,* as in figure 3-8. The filter choke provides a high impedance for *AC ripple* while having a relatively low DC resistance. Such a filter,

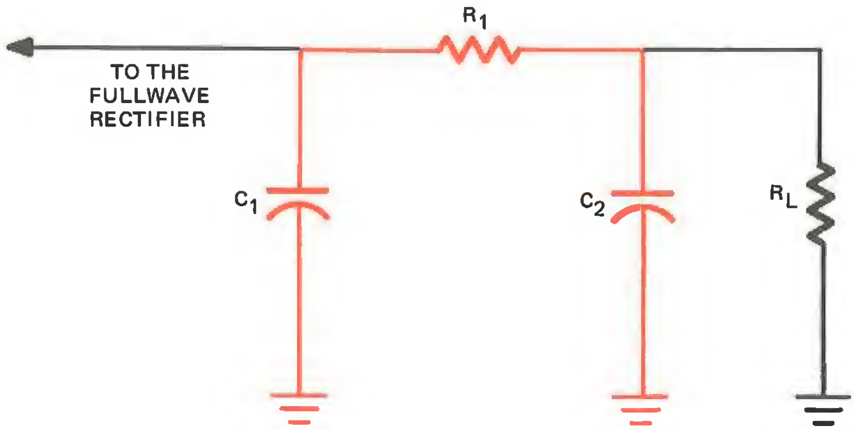


Fig. 3-7 A π Type Filter Circuit

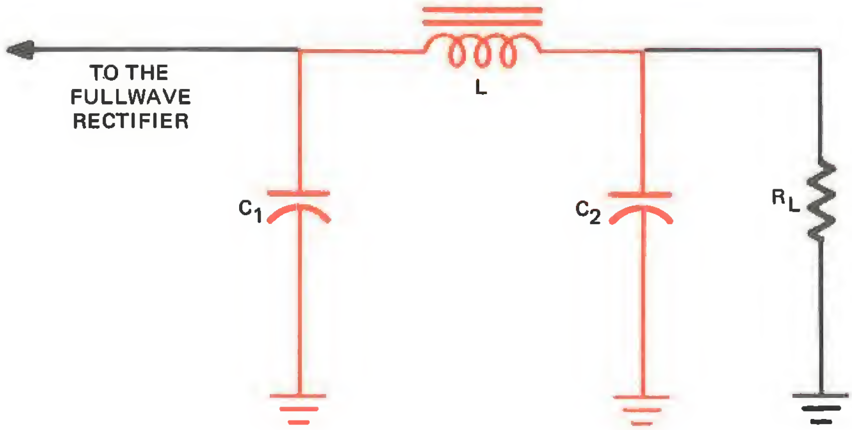


Fig. 3-8 A π Filter with an Inductor

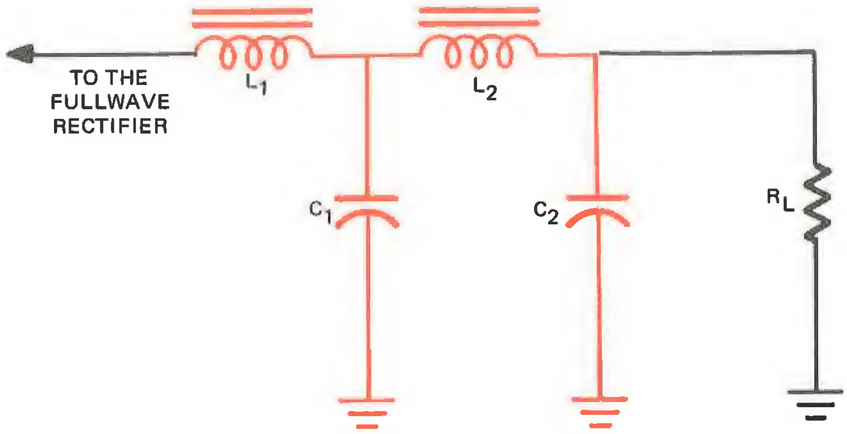


Fig. 3-9 A Double L-Section Filter

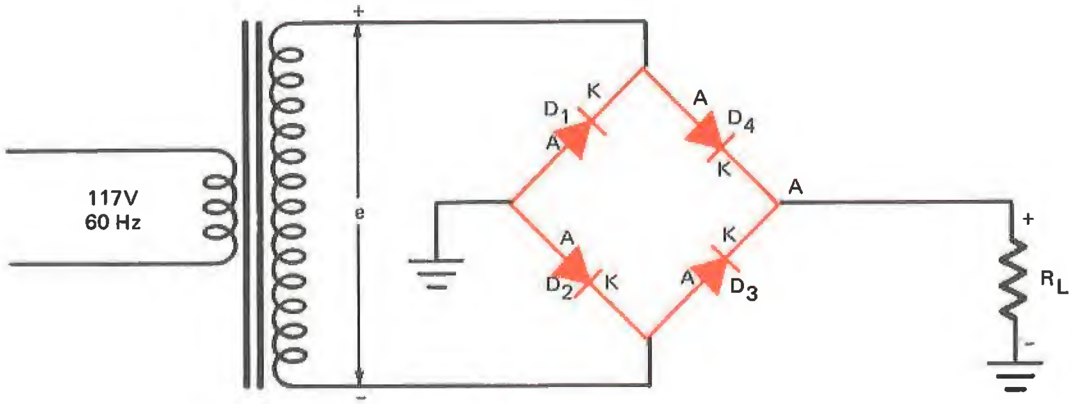


Fig. 3-10 A Fullwave Bridge Rectifier

while expensive, provides very good filtering action. When even better filtering is required, a second choke may be included, as seen in figure 3-9. When this input filter choke (L_1) is included, it also provides overcurrent protection for the diode, making R_1 unnecessary. Each LC pair (L_1C_1 and L_2C_2) is called an *L-section;* and in extreme cases, more than two sections may be used.

One of the small disadvantages of the fullwave rectifier shown in figure 3-1 is that it requires a center-tapped transformer. An alternate fullwave rectifier circuit which does not require such a transformer is shown in figure 3-10. This circuit is called a *Fullwave Bridge Rectifier.*

When the instantaneous transformer secondary polarity is as shown, the circuit current flows from the lower end of the transformer through D_2 to ground. (D_3 cannot conduct because it is reverse biased.) From ground, the current flows upward through the load to point A, then through D_4 to the top of the transformer.

On the alternate half of the input cycle, current flows through D_1, the load (upward), D_3 and back to the transformer. As a result, the load current waveform is the same as with the other fullwave circuit.

The same types of filter circuits are used with both types of fullwave rectifier circuits.

MATERIALS

1 Variable transformer (0 - 130V)
1 Transformer (110/220V CT)
4 Diodes, type 1N914 or equivalent
2 10 μF, 600W VDC capacitors
1 200Ω resistor 2W
1 Resistance substitution box (0 - 100 kΩ 2W)
1 FEM or VOM
1 Oscilloscope
2 Sheets of linear graph paper

PROCEDURE

1. Assemble the circuit shown in figure 3-11.
2. Adjust the input for 10 volts rms (AC) across one-half of the transformer secondary.
3. Determine and record the value of E_m.

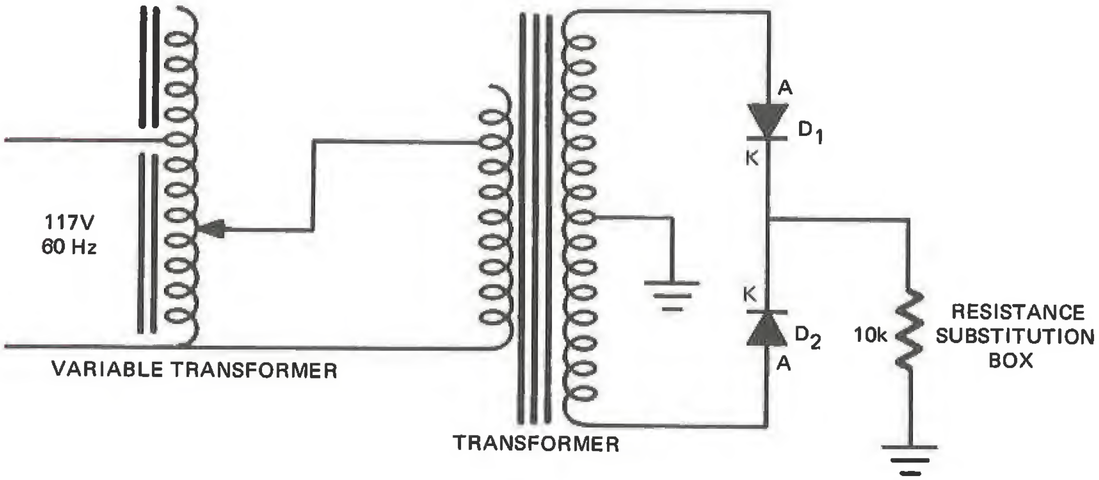


Fig. 3-11 The First Experimental Circuit

4. Using the appropriate equation in the discussion, compute and record E_{DC} and I_{DC}.
5. Measure and record the actual values of E_{DC} and I_{DC}.
6. With the oscilloscope, view the waveforms:
   (a) Across one-half of the transformer secondary
   (b) Across each diode
   (c) Across the load resistor.

   Make an accurate sketch of each waveform showing relative amplitude and phase relationships.
7. Connect the oscilloscope across the load and watch the change in waveform as a single 10 μF capacitor is connected across the load. Sketch the results.
8. Add a second 10 μF capacitor across the load, and sketch the resulting load voltage waveform.

9. Insert a 220-ohm resistor between the two capacitors forming a π section filter, and sketch the load voltage waveform.

10. Measure and record the values of E_{DC} and I_{DC} with the π filter in place.

11. Disassemble the first experimental circuit and construct the circuit shown in figure 3-12.

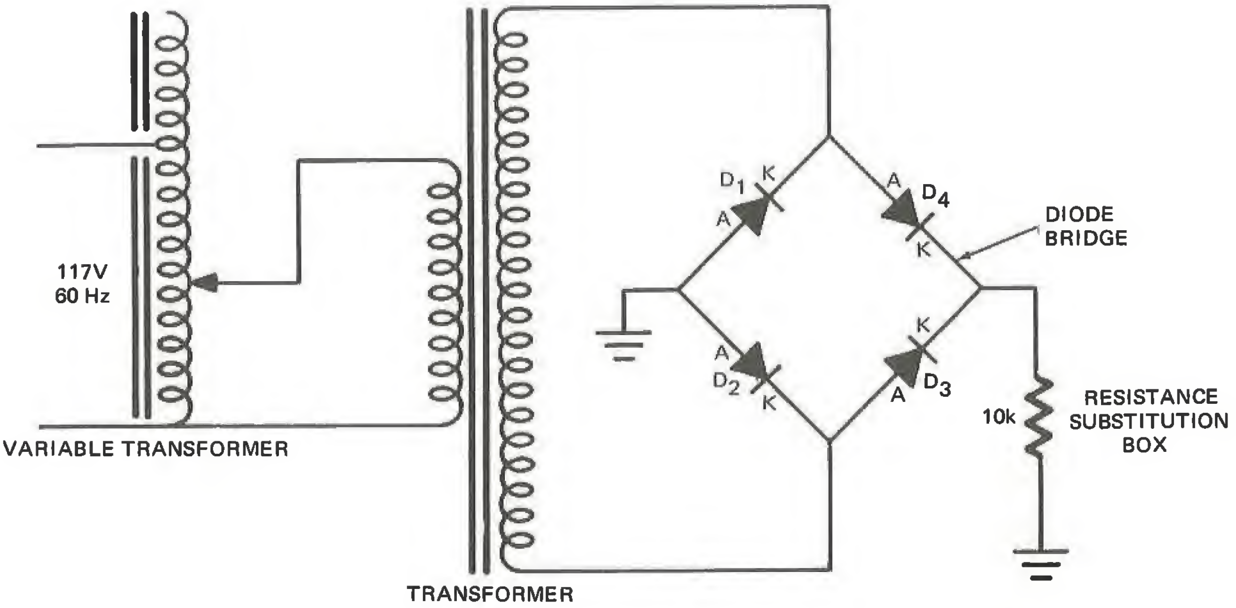


Fig. 3-12 The Second Experimental Circuit

12. Adjust the variable transformer for 10 volts rms across the transformer secondary and repeat steps 3 through 10.

Ckt.	E_m	E_{DC} (Comp)	I_{DC} (Comp)	E_{DC} (Meas)	I_{DC} (Meas)	E_{DC} (Filter)	I_{DC} (Filter)
First							
Second							

Fig. 3-13 The Data Table

ANALYSIS GUIDE. The purpose of this experiment has been to become familiar with the operation of fullwave rectifier circuits. Toward that end you should discuss *in your own words* how such a circuit works. Moreover, you should discuss the amount of agreement between your pairs of measured and computed values of E_{DC} and I_{DC}. Explain why the differences you observed seemed reasonable.

PROBLEMS

1. A fullwave rectifier (bridge circuit) is to be used without a filter to supply 15k VDC to an electrostatic air cleaner. If the system is to operate from a 117 VAC, 60-Hz line, what must be the transformer turns ratio?

2. What would have been the results in problem 1 if a filter which held the load voltage at the value of E_m were employed?

3. A certain unfiltered fullwave power supply (using 2 diodes only) operates from a 220 VAC, 60-Hz line. What would be the average current through a 780-ohm load if the transformer is center-tapped and has a turns ratio (N_p/N_s) of 4.0?

4. What would be the maximum *initial* charging current if a single 100 μF capacitor filter was attached to the power supply in problem 1? (Hint: Ignore the load and assume that the ripple frequency is 120 Hz during the *first* full cycle of operation. Also assume that the circuit resistance is close to zero.)

experiment 4 BIPOLAR TRANSISTOR OUTPUT CHARACTERISTICS

INTRODUCTION. The transistor is the basic amplifying device used in electronic circuits. In this experiment we shall examine the output terminal characteristics of two common categories of transistors.

DISCUSSION. Transistors may be classified into two distinct categories: *bipolar* devices which depend on the interaction of two types of charge carriers (holes and electrons), and *unipolar* devices which depend on a single type of charge carrier (holes or electrons).

Bipolar transistors were first introduced in 1948 and have since risen to a central position in electronics. Let us consider the pictorial representation of the *PNP transistor* shown in figure 4-1(a). (The schematic symbol is shown in figure 4-1(b). Notice that the righthand junction (between the N and P region marked *base* and *collector,* respectively) is reverse-biased. If we ignore the lefthand side for the moment, we see that the only current flowing across the base-collector junction would be the *reverse current* called I_{CO} in a transistor.

The lefthand junction (between the P and N regions designated *emitter* and *base* respectively) is forward-biased and there is hole flow from the emitter into the base region. If the base region is very thin (it is usually only

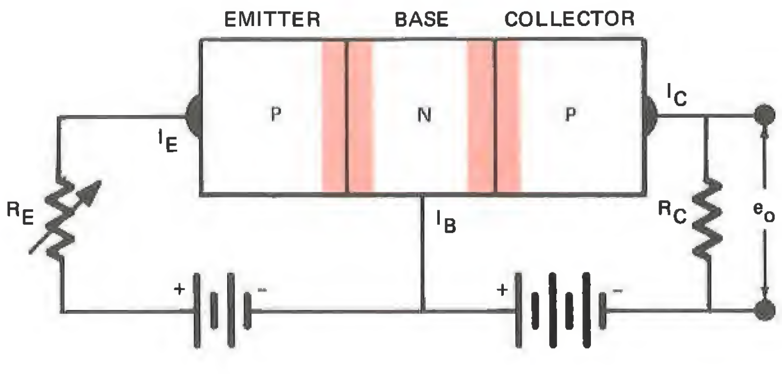


Fig. 4-1(a) Pictorial Representation of a PNP Transistor

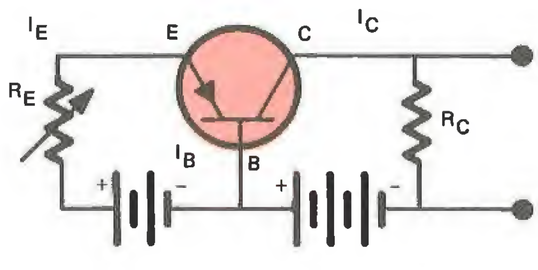


Fig. 4-1(b) Schematic Representation of PNP Transistor

a few microns thick in most transistors), then most of the holes which enter the base region (about 99% usually) are swept on across the base-collector junction and contribute to the *collector current* (I_C). Only a small portion of the *emitter current* (about 1%) flows in the base circuit.

In the PNP type transistor, figure 4-1(b), the holes are considered the *majority carriers.* It is equally practical to produce a second bipolar transistor using the NPN configuration shown in figure 4-2. The only major difference is that electrons are the majority carriers and the supply polarities are reversed from that of a PNP type transistor, as are the current flow directions.

If we consider the portion of the emitter current which contributes to the collector currents to be equal to $+\alpha_F I_E$, then the total collector current is

$$I_C = +\alpha_F I_E + I_{CO} \tag{4.1}$$

or

$$\alpha_F = +\frac{I_C - I_{CO}}{I_E}$$

However, when I_{CO} is very small compared to $I_C (I_C - I_{CO} \simeq I_C)$, then we have

$$\boxed{\alpha_F \simeq \frac{I_C}{I_E}} \tag{4.2}$$

In almost all practical cases, this approximation is reasonably valid.

Inspection of the transistor configuration reveals that there are six possible circuit arrangements. The three most important are: the common base connection shown in figures 4-1 and 4-2, the common collector connection, and the common emitter connection. These latter connections are shown in figures 4-3 and 4-4, respectively.

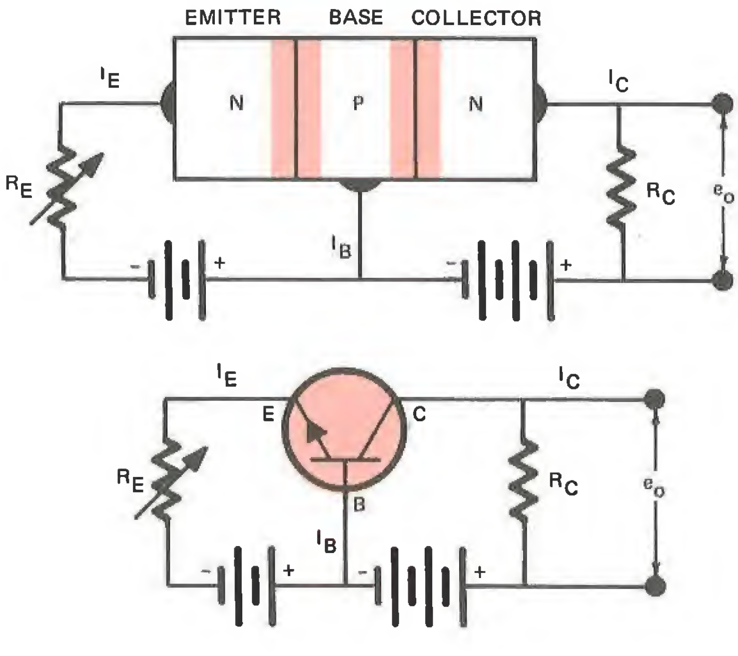
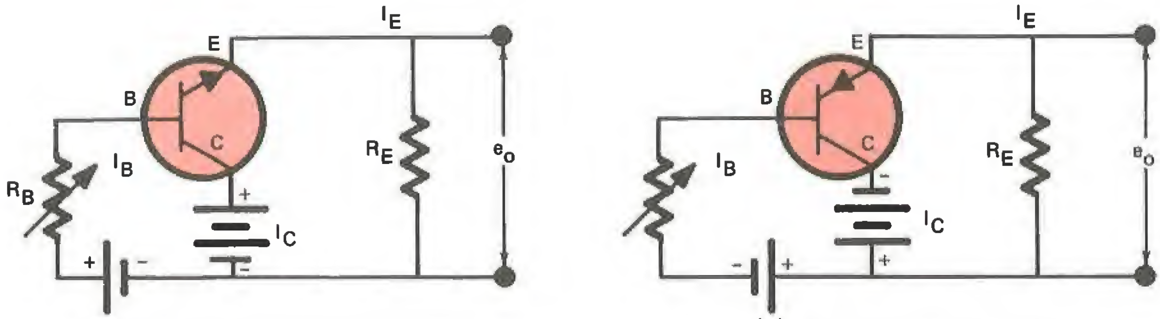
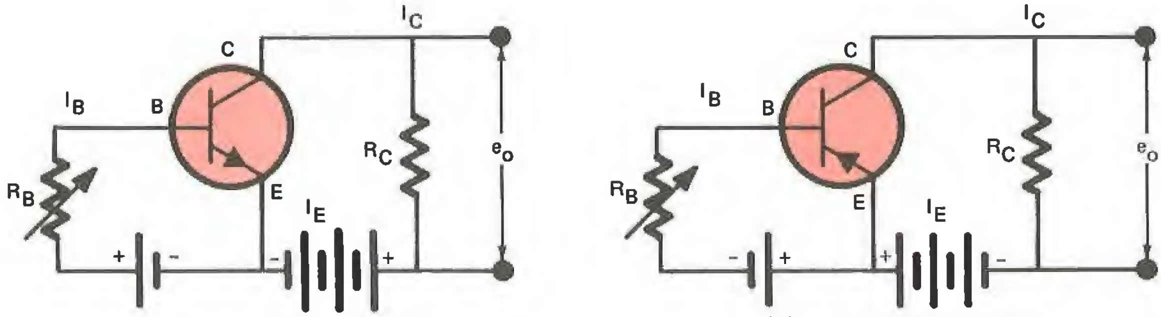


Fig. 4-2 Pictorial and Schematic Representation of an NPN Transistor



(A) NPN COMMON COLLECTOR *(B) PNP COMMON COLLECTOR*

Fig. 4-3 Transistors in Common Collector Configuration



(A) NPN COMMON EMITTER *(B) PNP COMMON EMITTER*

Fig. 4-4 Transistors in Common Emitter Configuration

In any case, the output current and, hence, the output voltage can be controlled by controlling the forward bias current on the base side of the transistor.

The common emitter circuit is by far the most frequently encountered circuit and will, therefore, be the only one dealt with further in this experiment.

As indicated in equation 4.1, the collector current in a transistor is

$$I_C = +\alpha_F I_E + I_{CO}$$

In most modern transistors I_{CO} is very near zero so we can often use the approximation

$$I_C \simeq \alpha_F I_E$$

From the common emitter configuration (figure 4-4), we see that

$$I_C + I_E + I_B = 0$$

or

$$I_E = -I_C - I_B$$

Substituting this quantity into equation 4.1 renders

$$I_C = \alpha_F I_C + \alpha_F I_B + I_{CO}$$

And collecting I_C terms on the left and factoring

$$I_C(1 - \alpha_F) = \alpha_F I_B + I_{CO}$$

or

$$I_C = \frac{\alpha_F}{1 - \alpha_F} I_B + \frac{1}{1 - \alpha_F} I_{CO} \qquad \textbf{(4.3)}$$

For a particular transistor, the term on the extreme right is relatively constant; and above this value, the collector current depends directly on the value of I_B. In many cases I_{CO} is almost zero. So we have

$$\boxed{I_C \simeq \frac{\alpha_F}{1 - \alpha_F} I_B} \qquad \textbf{(4.4)}$$

and the fraction $\alpha_F/1 - \alpha_F$ is sometimes called β_o or h_{fe}:

$$\boxed{\beta_o = \frac{\alpha_F}{1 - \alpha_F} = h_{fe}} \qquad \textbf{(4.5)}$$

If we plot the collector to emitter voltage (V_{CE}) versus the collector current (I_C), we will have the *output* or collector characteristics of the transistor in common emitter configuration. Figure 4-5 shows a typical output characteristic for this mode of operation.

Notice that at $I_B = 0\ \mu A$, the collector current depends on the term $I_{CO}/(1 - \alpha F)$. Above this very small value I_C is more or less linearly related to I_B at a given value of V_{CE}.

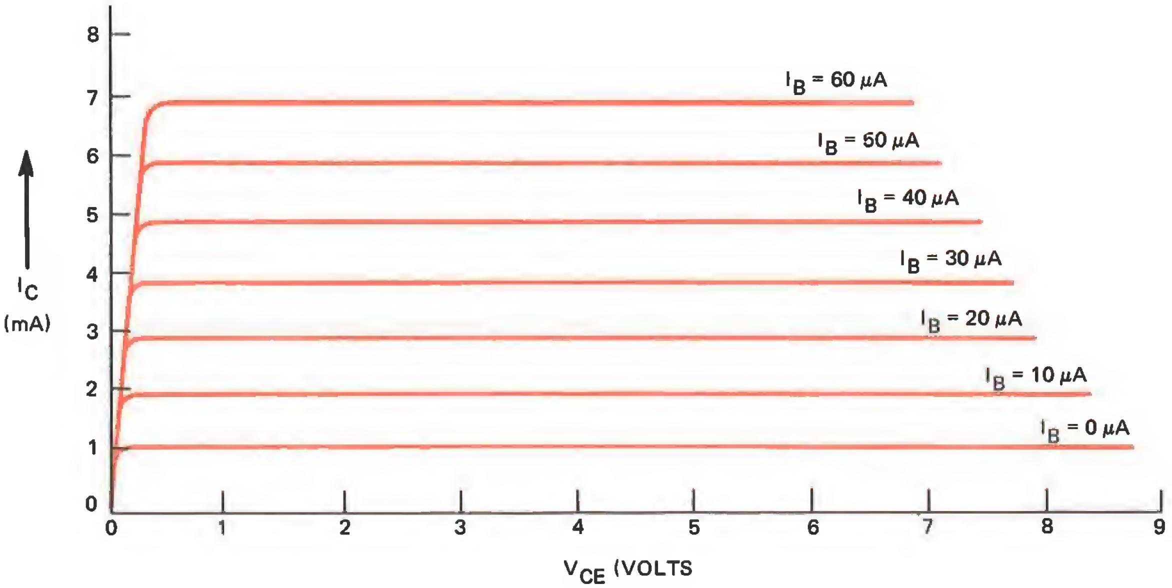


Fig. 4-5 Output Characteristics, Common Emitter Configuration

MATERIALS

- 2 Variable DC power supplies (0 - 40V)
- 3 VOMs or FEMs
- 1 PNP transistor, No. 2N1305 or equivalent
- 1 NPN transistor No. 2N1304 or equivalent
- 1 Transistor socket
- 1 1k 2W resistor
- 1 33k 1/4W resistor
- 2 Sheets of linear graph paper

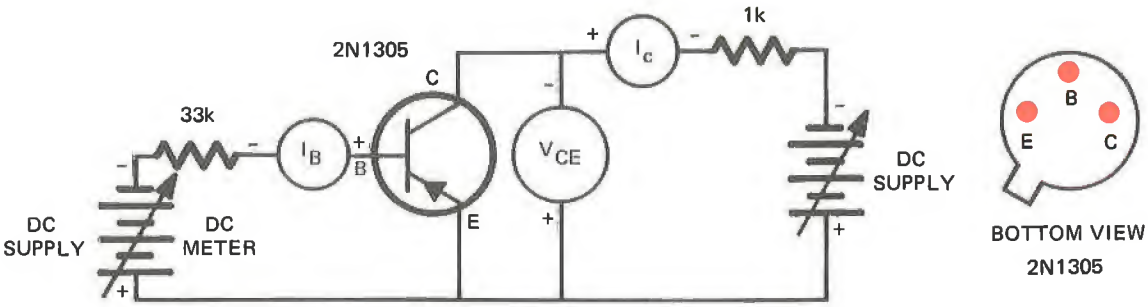


Fig. 4-6 The Experimental Circuit

PROCEDURE

1. Construct the circuit shown in figure 4-6 using the PNP transistor.
2. Set the base current (I_B) to zero. Measure and record the collector current (I_C) for collector-to-emitter voltages (V_{CE}) of 0, –1, –2, –4, –6, –8, –10, –12, –14, –16, –18, and –20 volts. **Be very sure that the base current and collector current values are read.**
3. Repeat the procedure followed in step 2 for base currents of 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 μA.

TRANSISTOR DATA

I_B (μA)	0	20	40	60	80	100	120	140	160	180	200
V_{CE} (volts)	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C
0											
–1											
–2											
–4											
–6											
–8											
–10											
–12											
–14											
–16											
–18											
–20											

Fig. 4-9 The First Data Table

4. On a sheet of graph paper plot the output characteristics of the device. Plot the characteristic in the first quadrant even though V_{CE} and I_C are negative values.

5. Repeat steps 1 through 4 using the NPN transistor. **Don't forget to reverse both power supplies.**

TRANSISTOR DATA

I_B (μA)	0	20	40	60	80	100	120	140	160	180	200
V_{CE} (volts)	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C
0											
-1											
-2											
-4											
-6											
-8											
-10											
-12											
-14											
-16											
-18											
-20											

Fig. 4-10 The Second Data Table

ANALYSIS GUIDE. In the analysis of these data you should consider the extent to which your output characteristics tend to verify the operation of the device as explained in the discussion.

To what extent is your curve similar to figure 4-5? How do they differ?

PROBLEMS

1. Using your curves, show how the value of I_{CO} for the PNP transistor can be determined.
2. How can the value of α_F for the PNP transistor be determined from your curves?
3. How does α_F compare between the two transistors?
4. How did the two sets of curves compare?

experiment 5 FIELD EFFECT TRANSISTOR OUTPUT CHARACTERISTICS

INTRODUCTION. The *transistor* is the basic amplifying device used in electronic circuits. In this experiment we shall examine the output terminal characteristics of one of the common categories of transistors, the field effect transistor.

DISCUSSION. Transistors may be classified into two distinct categories: *bipolar* devices which depend on the interaction of two types of charge carriers (holes *and* electrons), and *unipolar* devices which depend on a single type of charge carrier (holes *or* electrons).

The type of transistor to be considered in this experiment is the unipolar type. A unipolar transistor is a device which depends on only one carrier for its operation. The most commonly encountered unipolar semiconductor device is the *field effect transistor* (FET). This is represented pictorially in figure 5-1 and schematically in figure 5-2.

We observe from the pictorial that the PN junction (*gate* junction) is reverse-biased. Therefore, the only current flow in gate circuit is the small reverse current of the junction.

Electrons entering the left end of the device (the *source*) are drawn to the right end (*drain*) by the positive potential (E_{DS}). However, since no free carriers may flow through the depletion region around the gate junction, all of the drain current (I_D) must flow through the *channel* region. In a particular transistor the length of the channel will be more or less fixed. The cross-section of the channel will depend on the size of the depletion region and hence on the value of the gate bias. The channel is a conductive material, and its resistance will be directly related to the length of the channel and inversely related to the channel cross-section. In other words, the resistance from source to drain depends directly on the value of the gate bias (E_{GS}). For a given bias value, the drain current will be

$$I'_D = \frac{E_{DS}}{R_D} \tag{5.1}$$

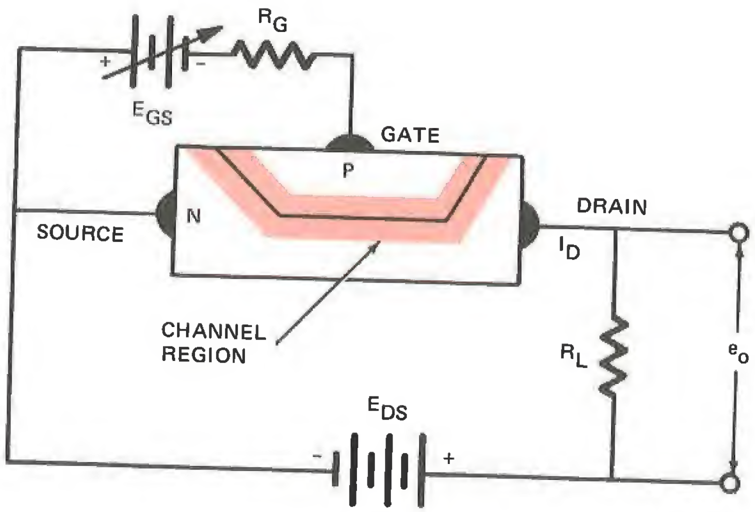


Fig. 5-1 Pictorial of an N-Channel FET

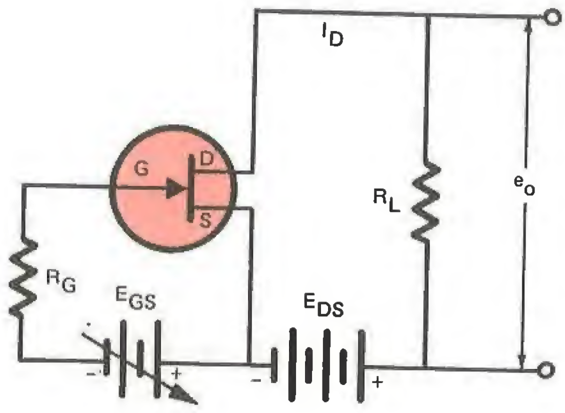


Fig. 5-2 Schematic of an N-Channel FET

We can define the relationship between a change in E_{GS} (ΔE_{GS}) and the resulting change in I_D (ΔI_D) as follows:

$$\frac{\Delta I_D}{\Delta E_{GS}} = g_m$$

or

$$\Delta I_D = g_m \, \Delta E_{GS}$$

where g_m is called the *forward transadmittance* or *transconductance* of the device. Now, if we allow the drain current to change by an amount equal to ΔI_D, then equation 5.1 becomes

$$I'_D + \Delta I_D = \frac{E_{DS}}{R_D} + \Delta I_D$$

And substituting $g_m E_{GS}$ for ΔI_D on the right and calling $(I'_D + \Delta I_D)$ the new total drain current (I_D), we have

$$I_D = g_m E_{GS} + \frac{E_{DS}}{R_D} \qquad (5.2)$$

From this equation we observe that if R_D is relatively constant, then when E_{GS} is zero, I_D will equal E_{DS}/R_D and any change of I_D from this value will be directly related to E_{DS}. Figure 5-3 shows the output characteristics of such a device.

It is important to notice that, in most practical devices, R_D is only relatively constant over small ranges of change of E_{GS}, E_{DS}, and I_D.

Many FETs have characteristics which are not so linear as the ones shown in figure 5-3. Usually the spacing between the lines tends to increase as I_D increases.

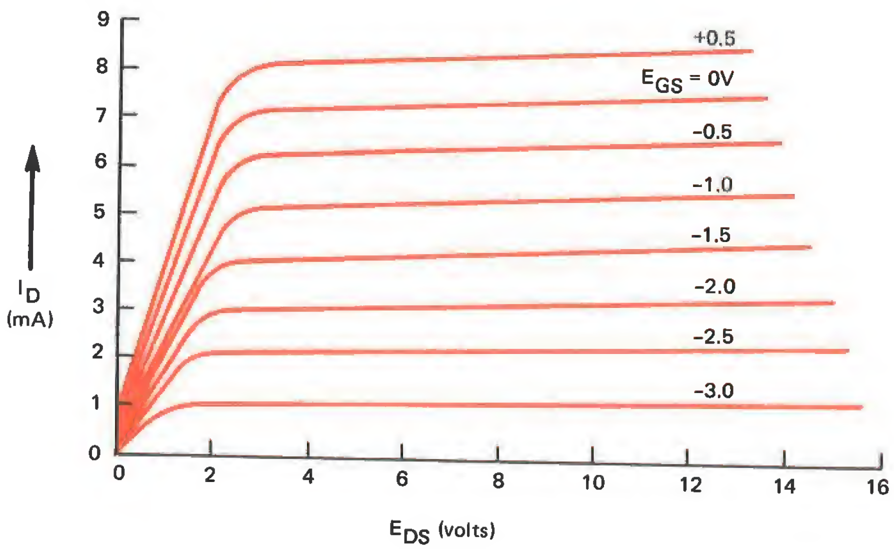


Fig. 5-3 Common Source Output Characteristics N-Channel FET

So far we have considered only the *N-channel* FET. It is equally possible to produce a *P-channel* device. The operation is the same, but the majority carriers are holes and all of the potential polarities and current directions are reversed from those of the N-channel diode.

Also, we have concentrated on a type of FET in which the gate voltage limits the current flow in the channel. Such a device is called a *depletion type* FET. A second type called an *enhancement type* FET is also used. In this case the gate potential enhances the value of the drain current rather than limiting it. Otherwise, the operation is very similar. Enhancement type FETs may be of either N-channel or P-channel construction just as in the case of the depletion type. However, enhancement types are constructed a little differently from the junction type discussed above.

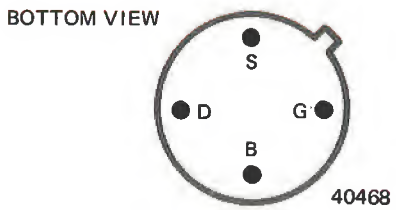
A more recent and currently very popular type of construction is the *insulated-gate* FET or MOSFET (the letters are for metal oxide semiconductor field effect transistor). In this type of construction, the gate region is electrically insulated from the channel material. The operation is much the same as a junction type FET, but the gate current is reduced to about 0.0001 μA. Some caution is necessary in handling MOSFETs as the gate insulation is *very* thin; so thin in fact that it can be destroyed *by touching the contacts with the bare hands.*

MATERIALS

2 Variable DC power supplies (0 - 40V)
3 VOMs or FEMs
1 N-channel, depletion type, MOSFET, Type 40468 or equiv.
1 Transistor socket
1 1k 2W resistor
1 33k 1/4W resistor
1 Sheet of linear graph paper

PROCEDURE

1. Examine the MOSFET and identify the drain, source, and gate leads using figure 5-4. *Notice* that the lead wires are twisted together (or otherwise short-circuited) to prevent electrostatic damage to the gate insulation. **Before handling the MOSFET, be very sure your body has not accumulated a high potential electrostatic charge. This can be avoided by holding a bare grounding strap while handling the FET.**



D = Drain, S = Source
G = Gate, B = Substrate and Case

Fig. 5-4 40468 Lead Connections

2. Leaving the gate (G) and case (B) leads shorted, connect the source (S), drain (D), and gate (G) leads in the circuit shown in figure 5-5. Then unshort the gate and case leads and connect the case lead (B) to the source.

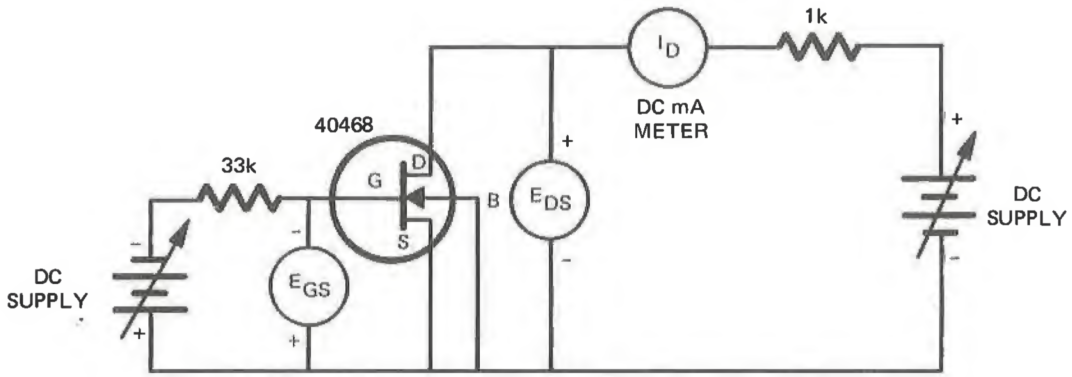


Fig. 5-5 The Experimental Circuit

3. Set the gate voltage (E_{GS}) to -5 volts. Measure and record the drain current (I_D) for drain-to-source voltages (E_{DS}) of 0, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 volts. **Be very sure that the gate and drain voltages are set to the prescribed values when each value of drain current is read.**

FET DATA

E_{GS} (volts)	-5.0	-4.5	-4.0	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	-0.0
E_{DS} (volts)	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D
0											
1											
2											
4											
6											
8											
10											
12											
14											
16											
18											
20											

Fig. 5-6 The Data Table

4. Repeat the procedure followed in step 3 for gate voltages (E_{GS}) of -4.5, -4.0, -3.5, -3.0, -2.5, -2.0, -1.5, -1.0, -0.5, and 0.0 volts.

5. Return both power supplies to zero. Disconnect the FET case lead (B) from the source (S) and twist it around the gate lead (G). Disconnect the drain, source, and gate leads and twist them all together. Disassemble the remaining circuitry.

6. On a sheet of graph paper plot the output characteristics of the device. Plot the characteristics in the first quadrant.

ANALYSIS GUIDE. In the analysis of these data you should consider the extent to which your output characteristics tend to verify the operation of the device as explained in the discussion.

To what extent is your curve similar to the one in figure 5-3? How do they differ?

PROBLEMS

1. Using your curves, show how the value of I_{DS} can be approximated if E_{DS} and E_{GS} are known.

2. How can the value of g_m for the FET transistor be determined from your curves? Does the part of the curve you use effect the value of g_m?

3. What was the approximate g_m value of the MOSFET used? (Use your curves to determine g_m.)

4. What region of the curve did you use in problem 3?

experiment 6 TRANSISTOR INPUT CHARACTERISTICS

INTRODUCTION. In any practical application of *transistors* it is necessary to supply appropriate input currents. For this reason the input characteristics of various *solid-state devices* are important. In this experiment we shall examine the input characteristics of typical bipolar and unipolar devices.

DISCUSSION. There are, of course, three possible transistor circuit configurations: *common base, common collector,* and *common emitter*. Since the common emitter configuration is by far the most frequently encountered, only it will be considered in this discussion. Let us consider the *NPN* common emitter circuit shown in pictorial and schematic form in figure 6-1.

If the electrode voltages (V_{BE} and V_{CE}) are constant, then the depletion regions at the junctions will be of constant width. The base-emitter depletion region will be quite narrow because of the forward bias. Any small change in base-emitter voltage will cause very small change in the width of that depletion region. We shall, therefore assume the base-emitter depletion region to have approximately constant width in the following discussion of the input characteristics.

On the other hand, the base-collector depletion region is relatively wide due to the reverse bias of that junction. As a result the "effective base width" is somewhat narrower than its actual physical width (the physical base width is typically only a few microns). Moreover, any increase in collector voltage will widen the base-collector depletion region and effectively make the base region even more narrow.

As a result of the reduced effective base width, an electron passing from emitter to base is even more likely to continue on to the

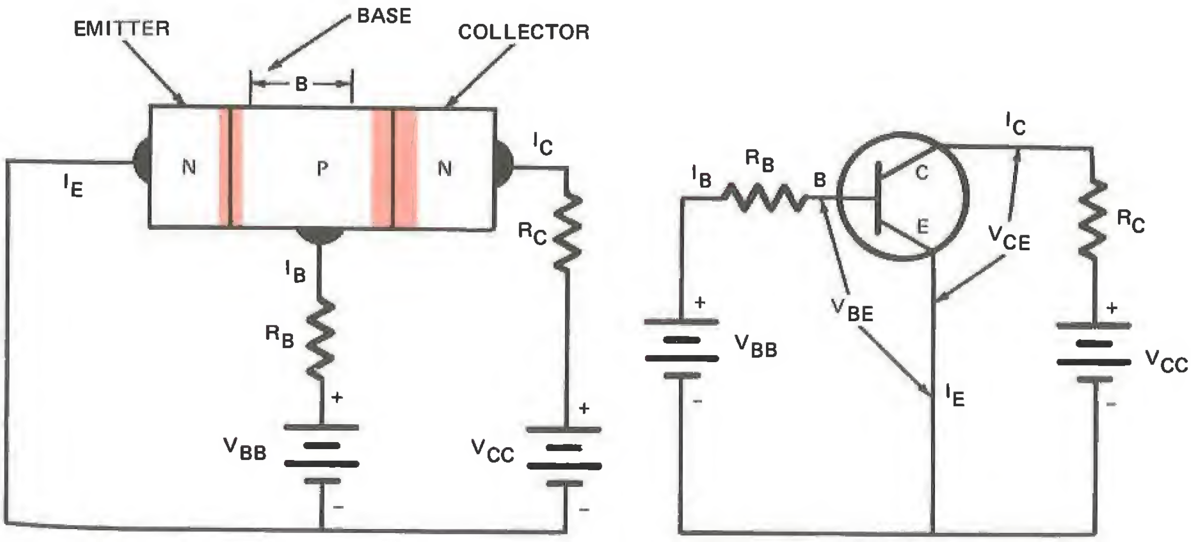


Fig. 6-1 An NPN Common Emitter Circuit

collector region than it was at a lower collector voltage. Since more of the emitter current tends to flow through the transistor to the collector, there are fewer electrons available to flow in the base circuit. As a result the *base current* tends to decrease with increasing *collector voltage,* provided that we hold the base voltage constant. If, on the other hand, we wish to maintain a constant base current, then we must increase the base voltage as the collector voltage is increased.

However, an increase of one volt in collector potential from V_{CE} = 1 volt to V_{CE} = 2 volts causes a much larger relative change in base width than does a change from V_{CE} = 10 volts to V_{CE} = 11 volts. Consequently, the required change in base voltage is *not* linearly related to the change in collector voltage.

The overall result of the discussion given above is reflected in figure 6-2 which is a typical NPN transistor input characteristic.

The voltages and currents would, of course, be reversed for a *PNP* type transistor.

Since the input characteristics of a transistor are essentially those of a forward-biased diode, we would expect them to present relatively low ohmic values. And indeed they typically run from about 1k to 10k ohms.

If we examine the input circuit of a field effect transistor circuit such as the one shown in figure 6-3, we see that the input characteristics are those of a *reverse-biased diode.* As such they tend to be about 10^8 ohms.

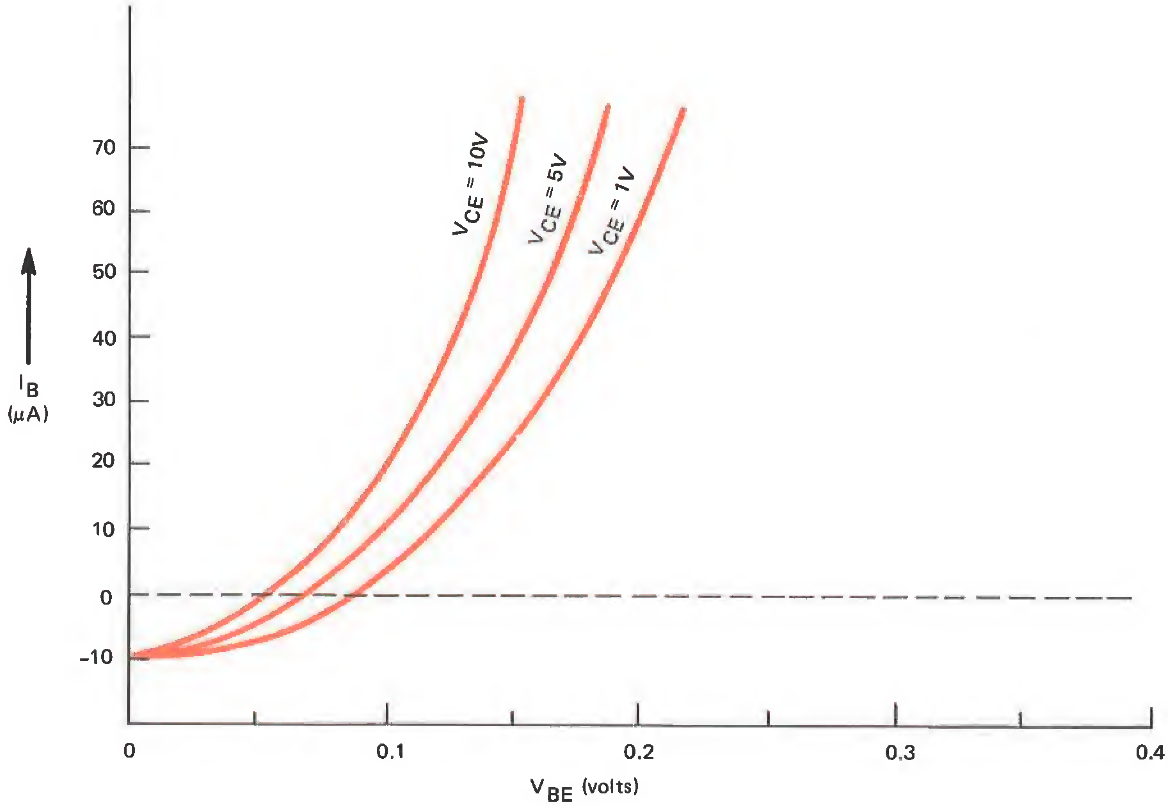


Fig. 6-2 A Typical NPN Transistor Input Characteristic

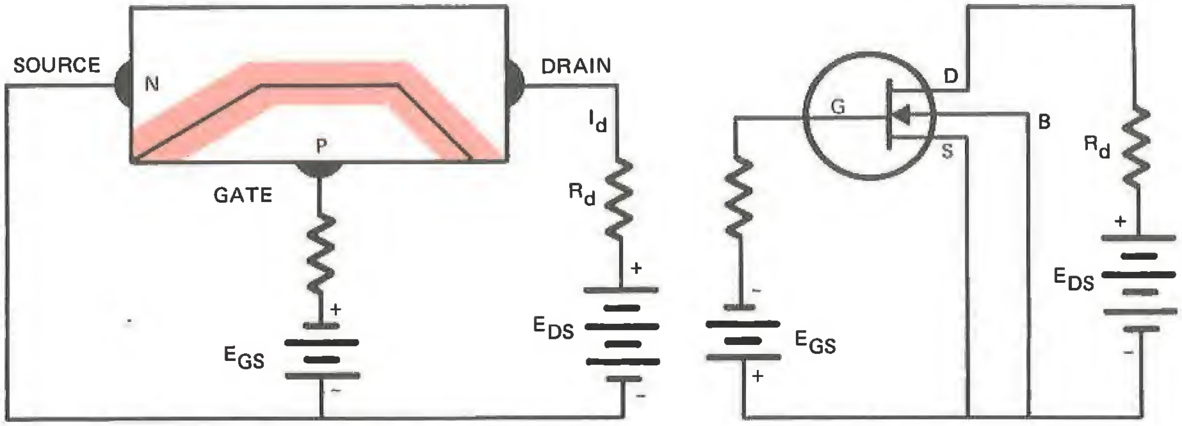


Fig. 6-3 A Common Source N-Channel FET

The MOSFET having an insulated gate junction tends to offer even higher input resistances (about 10^{10} to 10^{15} ohms in most cases). As a result the FET presents relatively few input resistance problems.

The overall conclusion that one should come to is that where *loading* is a problem, the FETs have the distinct advantage of very high input resistances. On the other hand, when dealing with sources which produce small *current* changes (such as strain gages, etc.), the low input resistance of the transistor offers a considerable advantage.

MATERIALS

- 2 Variable DC supplies (0 - 40V)
- 3 VOMs or FEMs
- 1 1k resistor 1/2W
- 1 33k resistor 1/2 W
- 1 PNP transistor, type 2N1305 or equivalent
- 1 MOSFET, type 40468 or equivalent
- 1 Transistor socket
- 1 Sheet of linear graph paper

PROCEDURE

1. Construct the circuit shown in figure 6-4 using the PNP transistor.

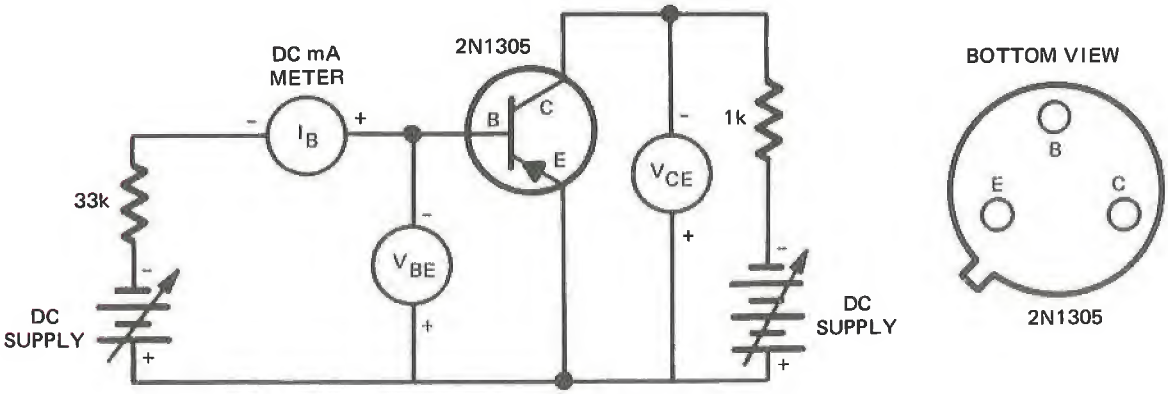


Fig. 6-4 The First Experimental Circuit

2. Set the collector voltage supply for a collector voltage of –1.0 volts.
3. Measure and record the base-emitter voltage for base currents of 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 μA. **Be sure that the collector voltage remains constant at the prescribed value.**
4. Repeat step 3 for collector voltages of -2.5, -5.0, -5.5, -10.0, -12.5, -15.0, -17.5 and -20.0 volts.
5. On a single sheet of graph paper plot the input characteristics of the transistor.
6. Disassemble the circuit shown in figure 6-3 and assemble the circuit shown in figure 6-4. **Observe the Appropriate Precautions to Prevent Electrostatic Damage to the Gate Insulation of the MOSFET.**
7. Set the drain voltage to +1.0 volts and the DC mA meter to its lowest range. Vary the gate voltage from 0 to -5V and record any indication on the DC mA meter. Prepare a data sheet if necessary.
8. Repeat step 7 for drain voltages of 5, 10, 15, and 20 volts.

V_{CE} (volts)	1.0	5.0	10.0	12.5	20.0
I_B (μA)	V_{BE}	V_{BE}	V_{BE}	V_{BE}	V_{BE}
0					
20					
40					
60					
80					
100					
120					
140					
160					
180					
200					

Fig. 6-5 The Data Table

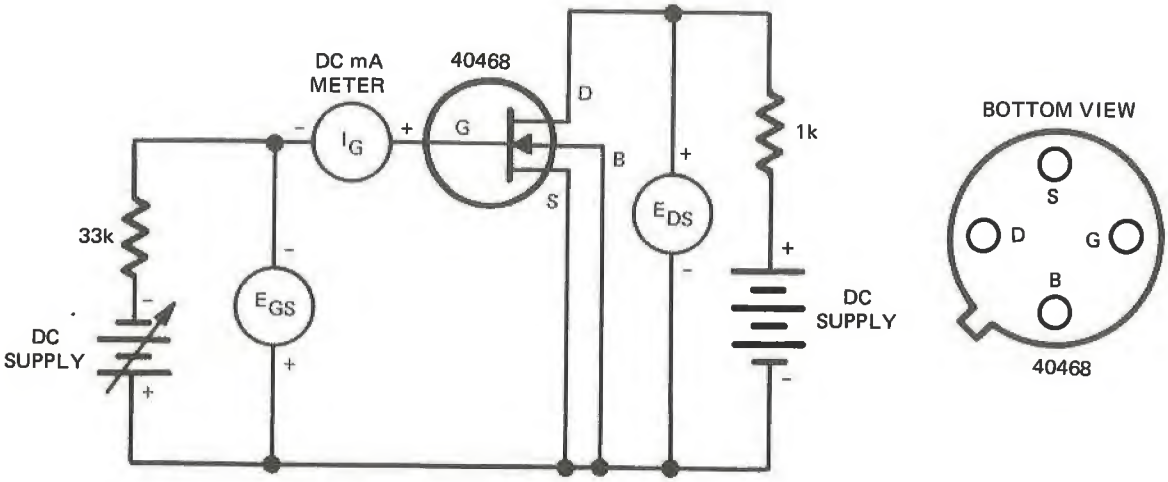


Fig. 6-6 The Second Experimental Circuit

9. Disassemble the circuit. **Observe the Appropriate Measures to Prevent Electrostatic Damage to the Gate Insulation of the MOSFET.**

ANALYSIS GUIDE. In analyzing these data compare the PNP transistor results to those described in the discussion. Explain the results you got with the FET and compare them with those from the PNP transistor.

PROBLEMS

1. Calculate the *approximate* value of the *static* input resistance of the PNP transistor.
2. Compute the *range* of the dynamic input resistance of the PNP transistor. What is the significance of *dynamic resistance* so far as a transistor is concerned?
3. If the input resistance of an FET were 10^{12} ohms, when would this become an important factor?
4. How does your input curve for the PNP transistor compare to figure 6-2?

experiment 7 TRANSISTOR LOADLINE ANALYSIS

INTRODUCTION. Transistors are widely used in all kinds of electronic applications. Before a transistor will function properly in a practical application, the DC electrode potentials must be established. In this experiment we shall explore how this can be accomplished in the common emitter circuit.

DISCUSSION. Let us consider the common emitter transistor circuit shown in figure 7-1. If we apply *Kirchhoff's voltage law* to the collector loop, we see that

$$V_{CC} - I_C R_L - V_{CE} = 0$$

or, if we solve for I_C, the result is

$$I_C = \frac{V_{CC} - V_{CE}}{R_L}$$

This may be rewritten in the form

$$\boxed{I_C = -\frac{1}{R_L} V_{CE} + \frac{V_{CC}}{R_L}} \qquad (7.1)$$

which we should recognize as a linear relationship (straight line) for I_C in terms of V_{CE}. (V_{CC} and R_L would both be constants in a practical case.)

For any specific transistor we will have another type of information relating I_C to V_{CE} in the form of the output characteristic. A typical example of such an output characteristic is shown in figure 7-2.

We can plot equation 7.1 on the output characteristic by observing that when V_{CE} in equation 7.1 is equal to zero, then

$$I_C = \frac{V_{CC}}{R_L} \text{ (when } V_{CE} = 0)$$

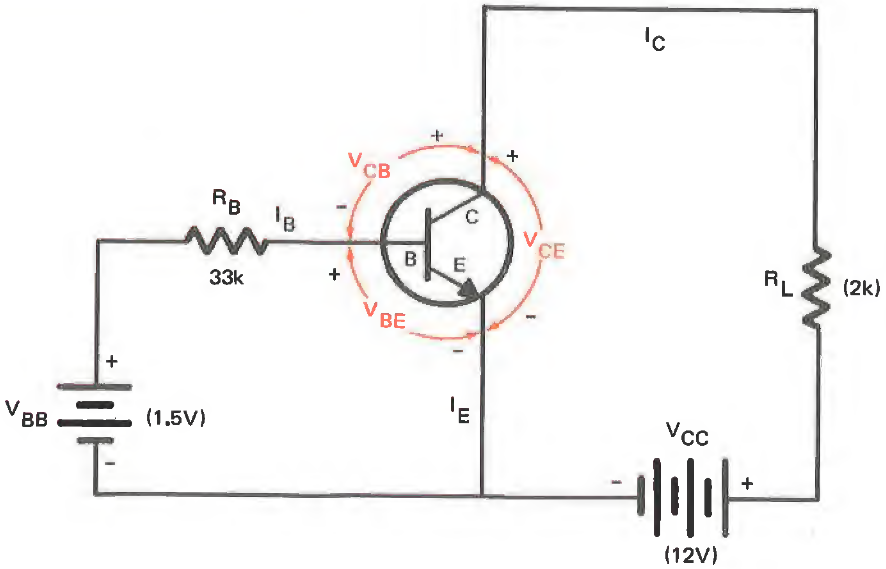


Fig. 7-1 A Common Emitter Amplifier

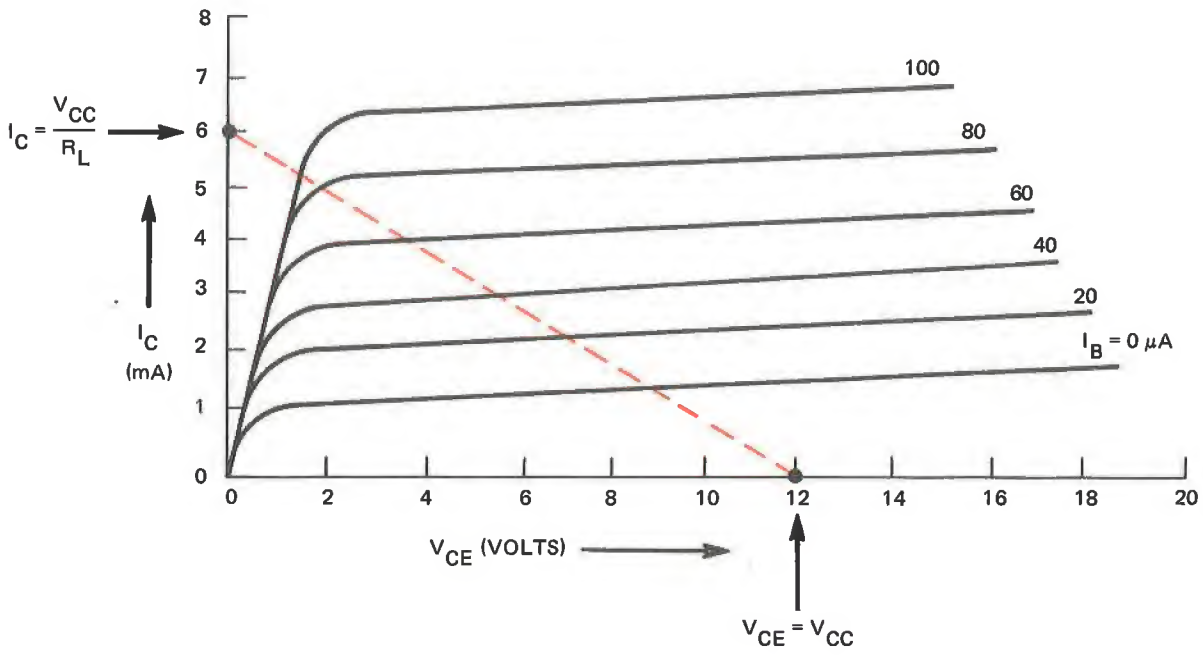


Fig. 7-2 A Typical NPN Common Emitter Output Characteristic

This point can be plotted at $V_{CE} = 0$ and $I_C = \frac{V_{CC}}{R_L}$ (12V/2k = 6 mA using values from figure 7-1) on the I_C axis line of the output characteristic.

Similarly, when I_C in equation 7.1 is zero, then we may solve for V_{CE} and get

$$V_{CE} = V_{CC} \quad (\text{when } I_C = 0)$$

This point can also be plotted on the characteristic curve. It is located on the V_{CE} axis line at V_{CC} (12 volts using the values in figure 7-1).

Now, since equation 7.1 represents a straight line, we can simply connect the two points already found (colored line in figure 7-2). This line is called the *loadline* of the 2k load resistor acting in series with the transistor T_1. *It represents all possible values of I_C which can flow through both the 2k load resistor and the transistor simultaneously* for the given value of (12V) of V_{CE}.

If we only knew the value of the base current, we could determine the value of I_C and V_{CE} for *this* transistor circuit. Consequently, the construction of the collector circuit loadline, as outlined above, is very important.

We may determine the value of base current in the circuit given in figure 7-1 by observing that the loop equation for the base circuit is

$$V_{BB} - I_B R_B - V_{BE} = 0 \qquad (7.2)$$

which may be solved for I_B, giving us

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

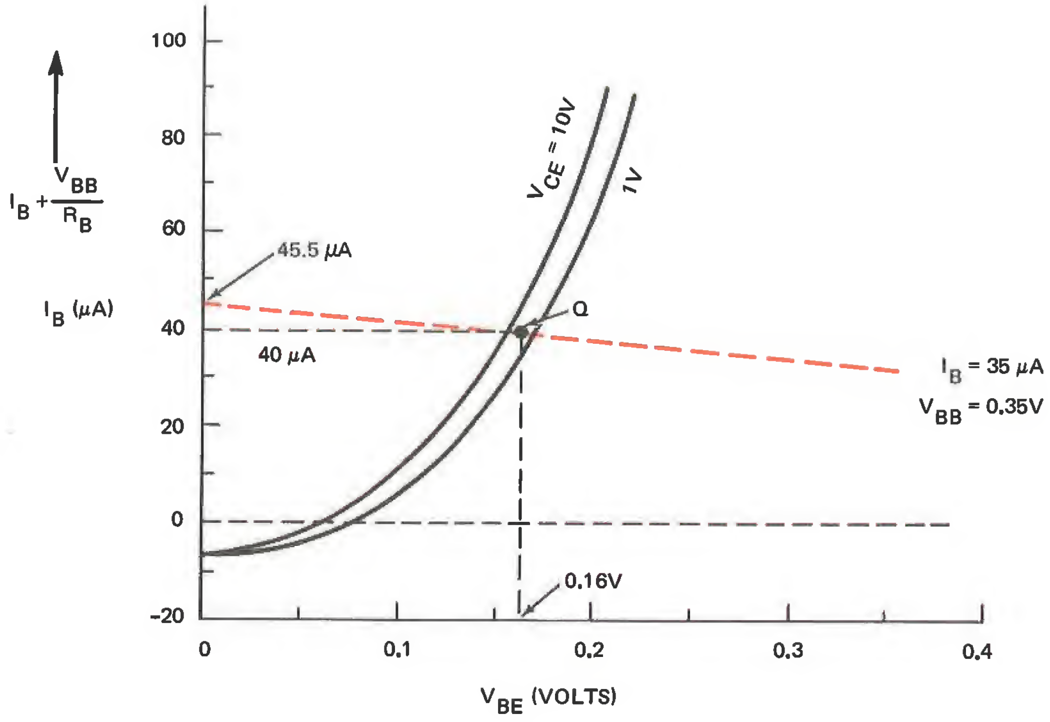


Fig. 7-3 A Typical NPN Common Emitter Input Characteristic

This equation may be rewritten in the form

$$\boxed{I_B = -\frac{1}{R_B}V_{BE} + \frac{V_{BB}}{R_B}} \qquad (7.3)$$

Notice that this is essentially the same form of equation as 7.1. We may therefore proceed just as in the construction of the collector circuit loadline. That is, if V_{BE} is equal to zero, then

$$I_B = \frac{V_{BB}}{R_B} \text{ (when } V_{BE} = 0)$$

This point may be plotted along the I_B axis of the *input characteristic* where $I_B = V_{BB}/R_B$. (1.5/33,000 = 45.5 μA using values from figure 7-1.) This point is shown plotted on the input characteristic in figure 7-3, the point where $V_{BE} = V_{BB}$ is usually far off of the input characteristic. It is common practice, therefore, to arbitrarily choose a value of base current (say 35 μA) and, using equation 6.2, solve for the corresponding value of V_{BE}:

$$V_{BE} = V_{BB} - I_B R_B \qquad (7.2)$$

In this case, $V_{BE} = 1.5 - 35 \times 10^{-6} \times 33 \times 10^3 \approx 0.35$ volts. The chosen value of I_B (35 μA) and the computed value of V_{BE} (0.35 volts) are then used to locate a second point on the base circuit loadline.

The base circuit loadline may then be drawn between the two identified points, as indicated in figure 7-3. At the point of intersection of the base loadline and the input characteristic curve (point Q in figure 7-3), we may read the values of I_B (40 μA) and V_{BE} (0.16V) for the circuit.

A second and much quicker method of arriving at a value for the base current is to

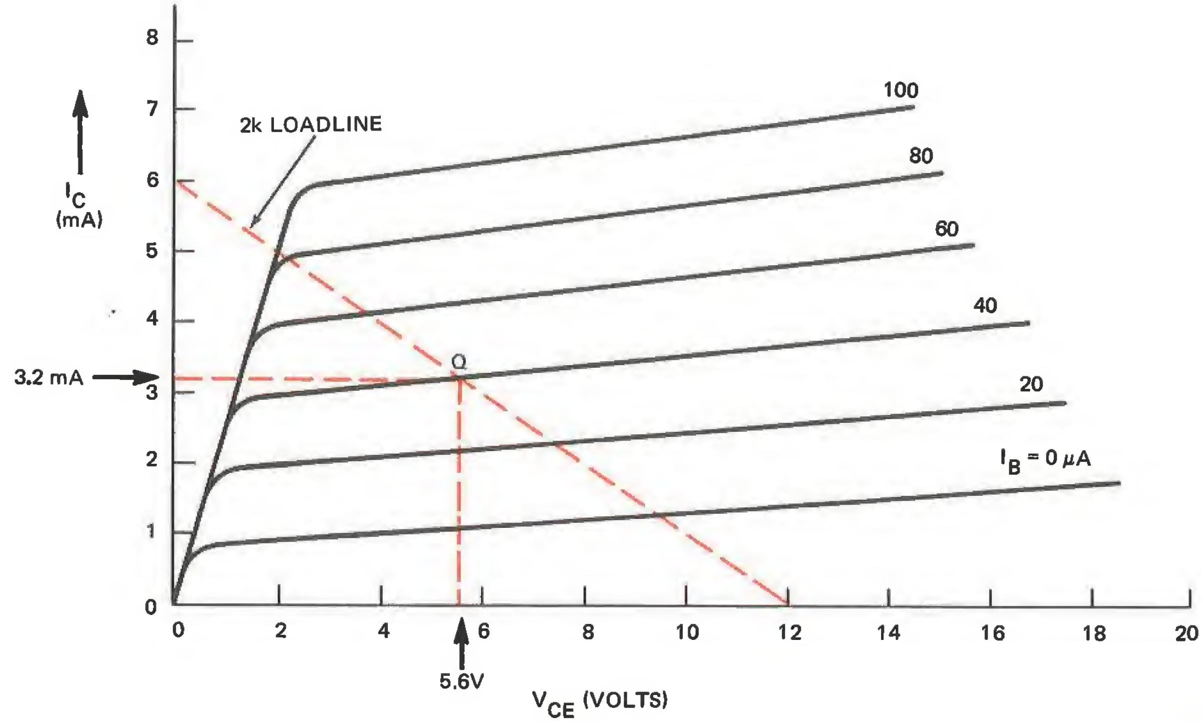


Fig. 7-4 Locating the Q Point on the Loadline

assume a value for V_{BE}. Use 0.2 volts for germanium transistors and 0.6 volts for silicon transistors. They are almost always near these values and can be used to solve for I_B using equation 7.3. The result in the case illustrated above would have been

$$I_c = -\frac{1}{R_B}V_{BE} + \frac{V_{BB}}{R_L} = 47.55\ \mu A$$

$$-6.05\ \mu A = 41.5\ \mu A \approx 40\ \mu A$$

With the value of the base current determined, we may return to the output characteristic and locate the actual *quiescent* operating point of the transistor. If we move up the loadline (see figure 7-4) until we reach the intersection with the appropriate base current line (40 μA in this example), we have located the quiescent operating point (Q). This is the only point on the output characteristic which simultaneously satisfies the requirements of both the collector and base circuits. At this point in figure 7-4 we see that I_C will be 3.2 mA and V_{CE} will be 5.6 volts. At the same time I_B will be 40 μA and V_{BE} will be 0.16 volts.

Returning to the original circuit of figure 7-1, we observe that

$$V_{CE} - V_{BE} - V_{CB} = 0 \qquad (7.4)$$

or

$$V_{CB} = V_{CE} - V_{BE}$$

In the example then

$$V_{CB} = 5.6 - 0.16 = 5.44 \text{ volts}$$

Similarly, we see that the terminal currents are related by

$$I_C + I_E + I_B = 0 \qquad (7.5)$$

or

$$I_E = -I_C - I_B$$

And using values of I_C and I_B found through loadline analysis

$$I_E = -3.2 \times 10^{-3} - 40 \times 10^{-6} = -3.24 \text{ mA}$$

By employing loadline analysis we are able to evaluate *all* of the transistor terminal voltages and currents. It also follows that the voltage across the collector resistor R_L is

$$E_L = I_C R_L = 3.2 \times 2 = 6.4 \text{ volts}$$

or, alternately,

$$E_L = V_{CC} - V_{CE} = 12.0 - 5.6 = 6.4 \text{ volts}$$

The close comparison between either of these two methods of calculating E_L indicates that our graphical analysis of the collector circuit was reasonably accurate.

Similarly, we may compute the value of the voltage across R_B using

$$E_B = I_B R_B = 40 \times 33 \times 10^{-3} = 1.34 \text{ volts}$$

or

$$E_B = V_{BB} - V_{BE} = 1.5 - 0.16 = 1.34 \text{ volts}$$

Once again the close agreement of the two methods indicates that our graphical analysis of the base circuit was accurate.

The analysis technique presented in this discussion is called *static loadline analysis* or *DC loadline analysis* and is one of the common methods of determining the DC operating voltages and currents in a transistor circuit.

MATERIALS

- 2 Variable DC supplies (0 - 40V)
- 2 Resistance substitution boxes (0 - 100k 2W)
- 2 VOMs or FEMs
- 1 PNP transistor type 2N1305 or equivalent
- 1 Transistor socket
- 1 Set of common emitter input and output characteristics for 2N1305

PROCEDURE

1. Examine the circuit shown in figure 7-5. Note the supply voltage polarities.

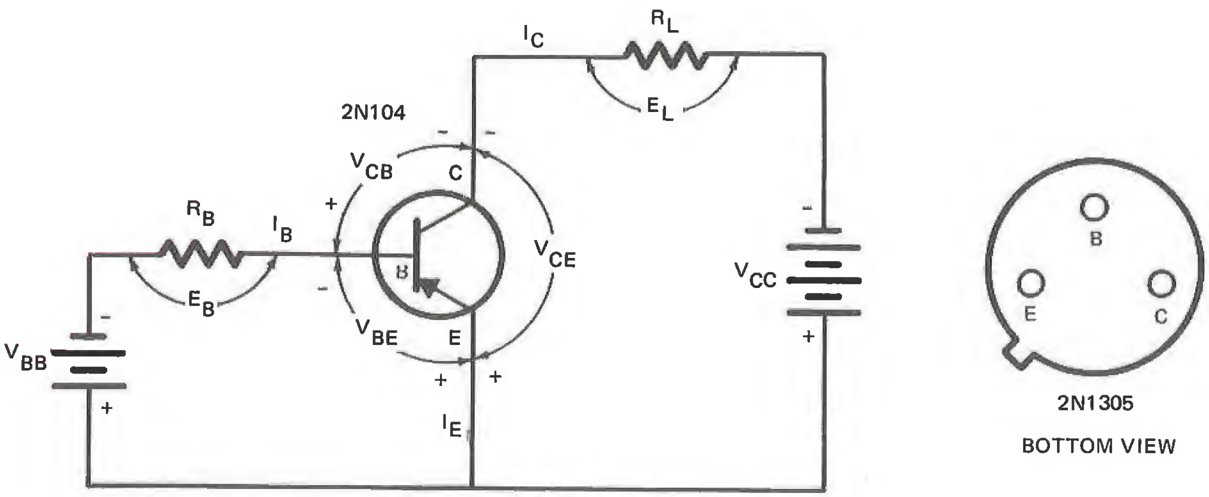


Fig. 7-5 The Experimental Circuit

2. Using the characteristic curves and assuming:

   V_{CC} = 10 volts V_{BB} = 1.5 volts R_L = 3.3k R_B = 47k

   Determine the values of I_C, V_{CE}, I_B, V_{BE}, I_E, V_{CB}, E_B, and E_L. Record the values as computed data in the data table.

3. Assemble the circuit using the values assumed in step 2. Use resistance substitution boxes for R_L and R_B.

4. Measure and record each of the values computed in step 2. (*Note:* I_B may be determined by measuring E_B, then using $I_B = E_B/R_B$).

5. Compute the percent difference between each pair of data values.

6. Repeat steps 2 through 5 using:

   V_{CC} = 12 volts R_L = 4.7k

   V_{BB} = 2.0 volts R_B = 68k

7. Similarly, repeat steps 2 through 5 using:

   V_{CC} = 9 volts R_L = 2.2k

   V_{BB} = 1 volt R_B = 33k

Circuit Conditions	V_{CC} = 10V, V_{BB} = 1.5V				R_L = 3.3k, R_B = 47k			
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Circuit Conditions	V_{CC} = 12V, V_{BB} = 2.0V				R_L = 4.7k, R_B = 68k			
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Fig. 7-6 The Data Tables

Circuit Conditions			V_{CC} = 9V			R_L = 2.2k		
			V_{BB} = 1V			R_B = 33k		
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Fig. 7-6 The Data Tables (Cont'd)

8. Include your characteristic curves as part of the data and clearly identify each loadline and each Q point.

ANALYSIS GUIDE. In analyzing these data you should consider primarily the reliability of the loadline method of circuit analysis, how well your measured and computed values agreed, and how your computational accuracy could have been improved.

PROBLEMS

1. What was the static output resistance of the transistor at each Q point?
2. What was the dynamic output resistance at each Q point?
3. What was the static and dynamic input resistance of the transistor at each of the Q points?
4. What is the importance of the dynamic input resistance of a transistor?

experiment 8 BIASING AND BIAS STABILITY

INTRODUCTION. If the loadline analysis of a transistor is to be reliable, then the *quiescent point* must be *fixed*. In this experiment we shall consider methods of establishing the quiescent point and holding it in position.

DISCUSSION. Let us consider the common emitter circuit shown in figure 8-1. Under normal operating conditions, the output characteristic (with collector circuit loadline) is as pictured in figure 8-2, and the net collector current is

$$\boxed{I_C = -\alpha_F I_E + I_{CO}} \qquad (8.1)$$

where α_F is the ratio of the emitter current which flows in the collector circuit to the total emitter current.

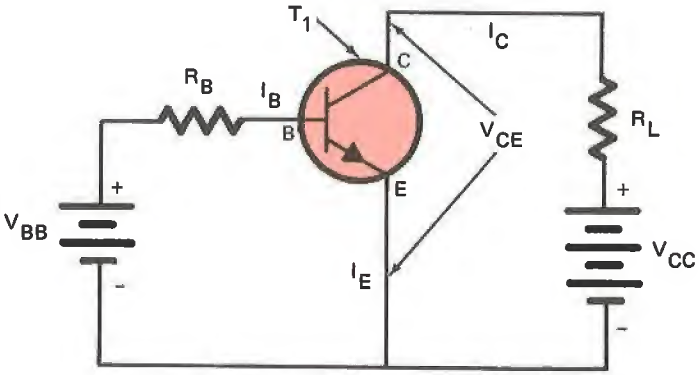


Fig. 8-1 A Common Emitter Transistor Circuit

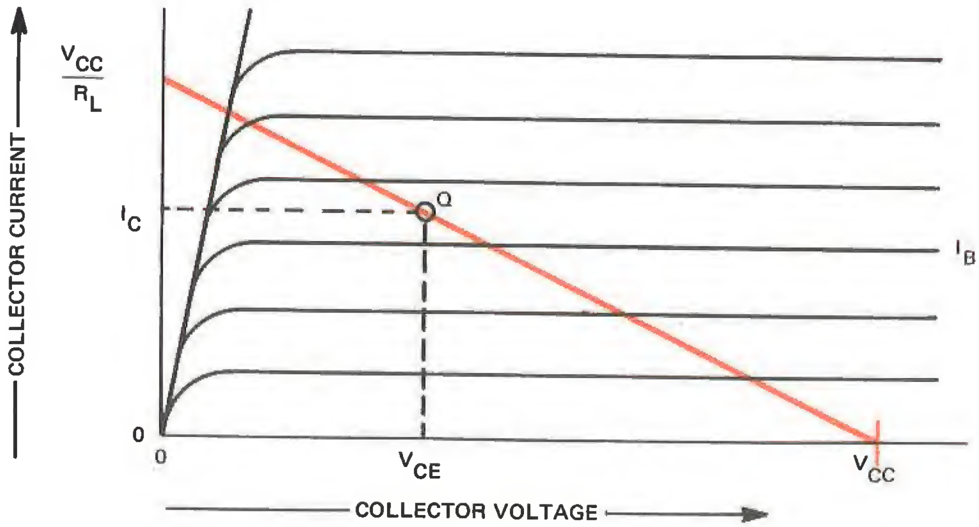


Fig. 8-2 A Typical Output Characteristic

But from figure 8-1, we see that

$$I_E + I_C + I_B = 0$$

or

$$I_E = -(I_C + I_B)$$

Substituting this quantity into equation 8.1 for I_E renders

$$I_C = \alpha_F I_C + \alpha I_B + I_{CO}$$

or

$$I_C(1 - \alpha_F) = \alpha_F I_B + I_C$$

and

$$I_C = \frac{\alpha_F I_B + I_{CO}}{1 - \alpha_F}$$

This may be rewritten in the form

$$I_C = \frac{\alpha_F}{1 - \alpha_F} I_B + \frac{1}{1 - \alpha_F} I_{CO} \qquad \textbf{(8.2)}$$

which is the equation usually given for the collector current of a common emitter circuit. *A typical value for α_F is 0.99;* therefore, equation 8.2 typically reduces to something like

$$I_C \approx 100 I_B + 100\ I_{CO}$$

From this typical relationship, we see that if I_B is constant, then any small change in I_{CO} will be reflected a hundred times greater in I_C.

I_{CO} is the reverse bias current across the base-collector junction. If we raise the temperature of the transistor, then more carriers become available in the transistor material and I_{CO} tends to increase. This increase in I_{CO} shifts the entire output characteristic upward as shown in figure 8-3 (colored lines).

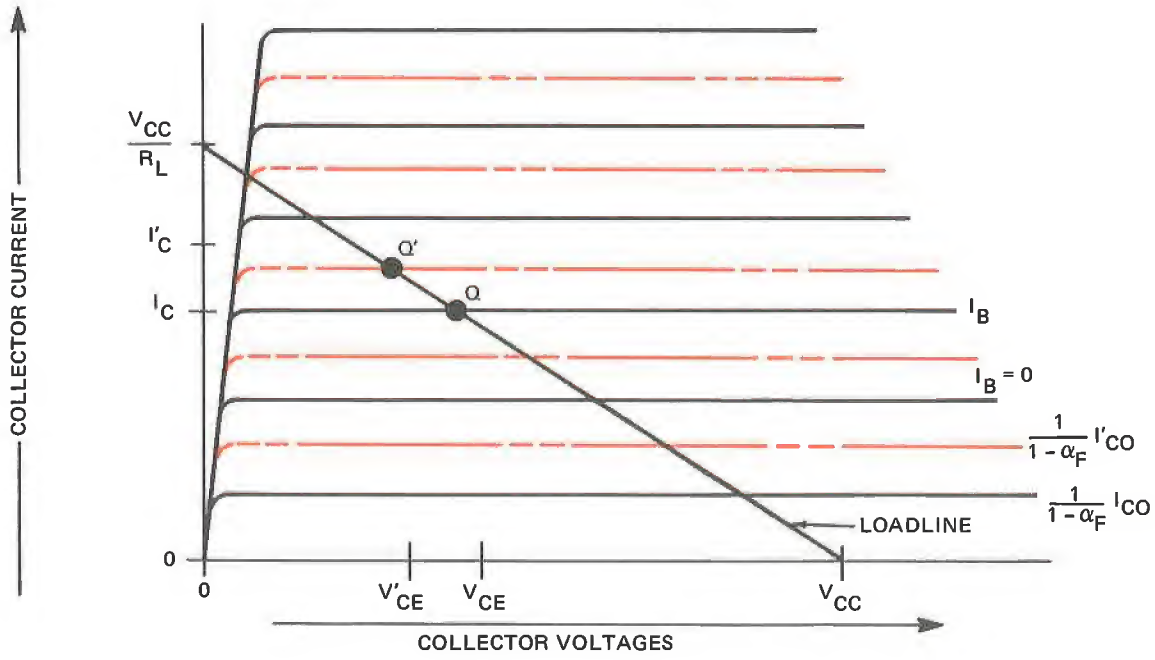


Fig. 8-3 Shift in Q-Point with Temperature

As the characteristics shift, the Q-point must also shift from its original location (Q) on the loadline to a new location (Q'). As a result both I_C and V_{CE} must also shift to new values, I'_C and V'_{CE}.

The ratio of the change in I_C for a given change in I_{CO} is called the *stability factor* (S) of the circuit. From the above discussion, we can see that the stability factor is

$$\boxed{S = \frac{dI_C}{dI_{CO}} = \frac{1}{1 - \alpha_F} \simeq \frac{\Delta I_C}{\Delta I_{CO}}} \qquad (8.3)$$

Using the values cited before, we would have

$$S = \frac{100}{1} = 100$$

A transistor circuit with a poor stability factor (large change in I_C for small I_{CO} change) can cause severe problems. For example, suppose the circuit discussed above is subjected to a sudden change in temperature (perhaps by a nearby soldering iron) and I_{CO} increases a small amount. The value of I_C increases proportionally which generates more heat ($I_C{}^2 R_C$) inside the transistor. I_{CO} will therefore continue to rise and I_C along with it until the transistor is finally damaged (or destroyed) by its own internal heat. This condition is called *thermal runaway* and does occur in poorly stabilized circuits.

To improve the stability factor of transistor circuits, a resistor is frequently inserted in the emitter lead of the transistor as shown in figure 8-4. To see how this improves the stability factor, let us observe that the input loop equation is now

$$V_{BB} - I_B R_B - V_{BE} + I_E R_E = 0 \qquad (8.4)$$

However, we recall that equation 8.2 is

$$I_C = \frac{\alpha_F}{1 - \alpha_F} I_B + \frac{1}{1 - \alpha_F} I_{CO}$$

or

$$I_C(1 - \alpha_F) = \alpha_F I_B + I_{CO}$$

which may be solved for I_B rendering

$$I_B = \frac{1 - \alpha_F}{\alpha_F} I_C - \frac{1}{\alpha_F} I_{CO} \qquad (8.5)$$

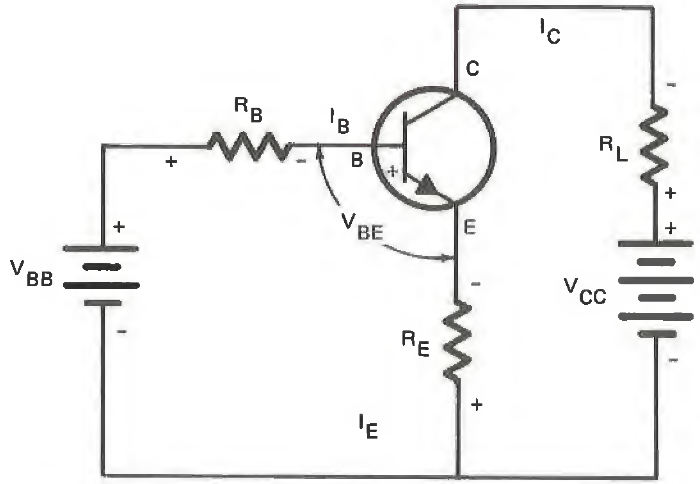


Fig. 8-4 A Stabilized Transistor Circuit

Also equation 8.1

$$I_C = -\alpha_F I_E + I_{CO}$$

may be solved for I_E giving us

$$I_E = \frac{1}{\alpha_F} I_{CO} - \frac{1}{\alpha_F} I_C \qquad (8.6)$$

Substituting the two values (I_B and I_E) into equation (8.4) provides

$$V_{BB} - \frac{1-\alpha_F}{\alpha_F} I_C R_B - \frac{R_B}{\alpha_F} I_{CO} - V_{BE}$$

$$+ \frac{R_E}{\alpha_F} I_{CO} - \frac{R_E}{\alpha_F} I_C = 0$$

which may be solved for I_C rendering

$$I_C = \frac{\alpha_F(V_{BB} - V_{BE}) - I_{CO}(R_E + R_B)}{R_E + R_B(1-\alpha_F)}$$

which may be rewritten as

$$I_C = \frac{\alpha_F(V_{BB} - V_{BE})}{R_E + R_B(1-\alpha_F)} - \frac{R_E + R_B}{R_E + R_B(1-\alpha_F)} I_{CO}$$

Now, if V_{BB}, α_F, V_{BE}, R_B, and R_E are all constant, then the first term above is a constant and any change in I_C must be caused by a change in I_{CO}. We may therefore write

$$\Delta I_C = \frac{R_E + R_B}{R_E + R_B(1-\alpha_F)} \Delta I_{CO}$$

and since

$$\boxed{S \simeq \frac{\Delta I_C}{\Delta I_{CO}}}$$

we have

$$\boxed{S \simeq \frac{R_E + R_B}{R_E + R_B(1-\alpha_F)}} \qquad (8.7)$$

Remember that in the previous example the change in I_C was 100 times the change in I_{CO}, or, in other words, S *was* equal to 100. (α_F was 0.99.) Let us now suppose that R_B = 10k and R_E = 1k are used in the same circuit. S now becomes

$$S \simeq \frac{R_E + R_B}{R_E + R_B(1-\alpha_F)} = \frac{11}{1 + 10(0.01)} = \frac{11}{1.1} = 10$$

We have, therefore, improved the stability factor considerably by inserting the 1k emitter resistor. In typical circuits, values for S normally range from about 5 up to about 20.

Up to this point, we have always considered circuits biased in the manner shown in figure 8-1 using a separate base bias supply V_{BB}. While such a circuit is easy to analyze, it is not very practical because it requires two power supplies (V_{BB} and V_{CC}). A much more practical and consequently frequently encountered method is the single supply circuit shown in figure 8-5.

This practical transistor bias network may be readily reduced to the simpler two battery equivalent by Thévenizing the circuit to the left of the points X, X. Disconnecting the circuit at these points, we see that the equivalent bias battery voltage would be

$$V_{BB} = V_{CC} \frac{R_2}{R_1 + R_2} \qquad (8.8)$$

and the Thévenin's source resistance (R_B) would be the parallel combination of R_1 and R_2,

$$R_B = \frac{R_1 R_2}{R_1 + R_2} \qquad (8.9)$$

For purposes of analysis it is often convenient to replace the practical single supply bias net-

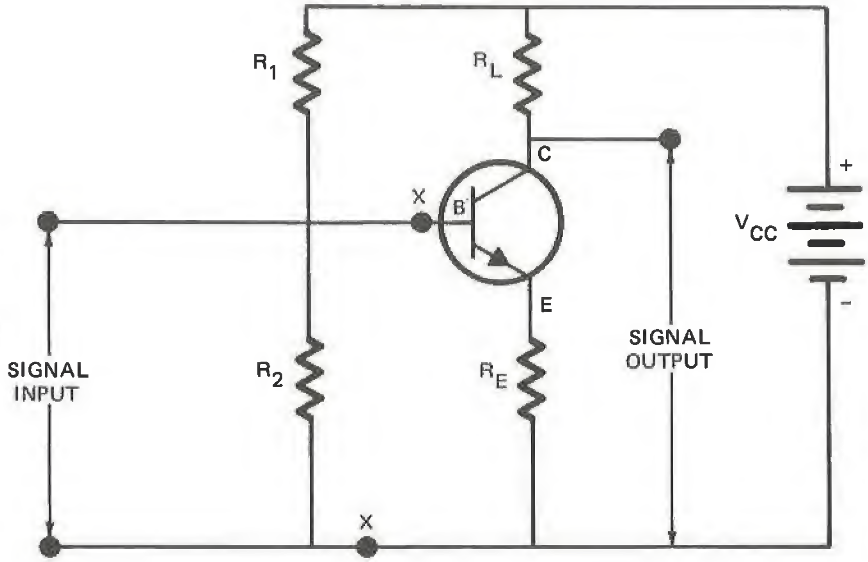


Fig. 8-5 The Single Supply Transistor Circuit

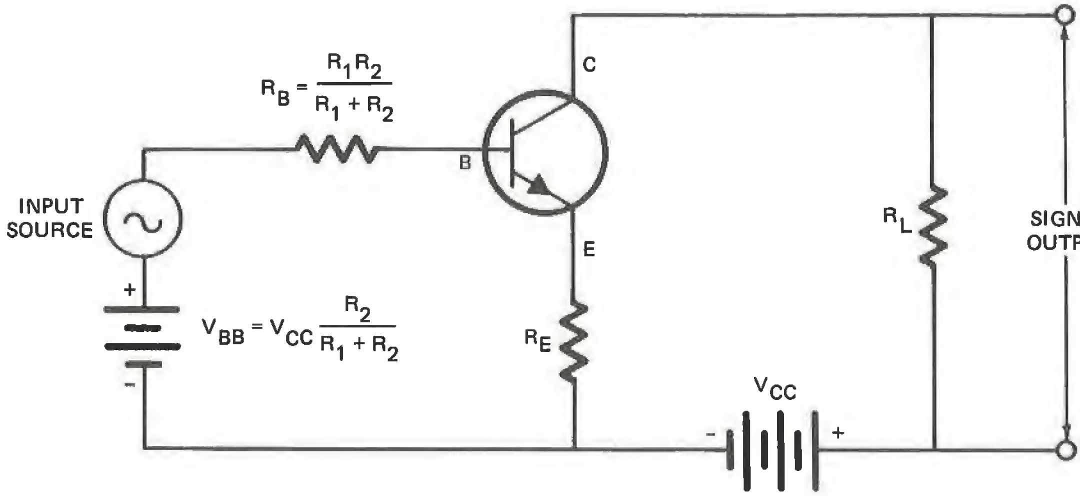


Fig. 8-6 The Two-Battery Equivalent of Figure 8-5

work with its equivalent two-battery circuit as shown in figure 8-6.

Although this discussion has featured NPN transistors throughout, the results are equally appropriate for either NPN or PNP types.

MATERIALS

2 Resistance substitution boxes (0 - 10 meg 1/2W)
1 1k resistor 1/2W
1 5.6k resistor 1/2W
1 33k resistor 1/2W
1 2N1305 transistor or equivalent
2 DC supplies (0–40V)
2 VOMs or FEMs
1 Soldering iron (approximate 35W)
1 Transistor socket

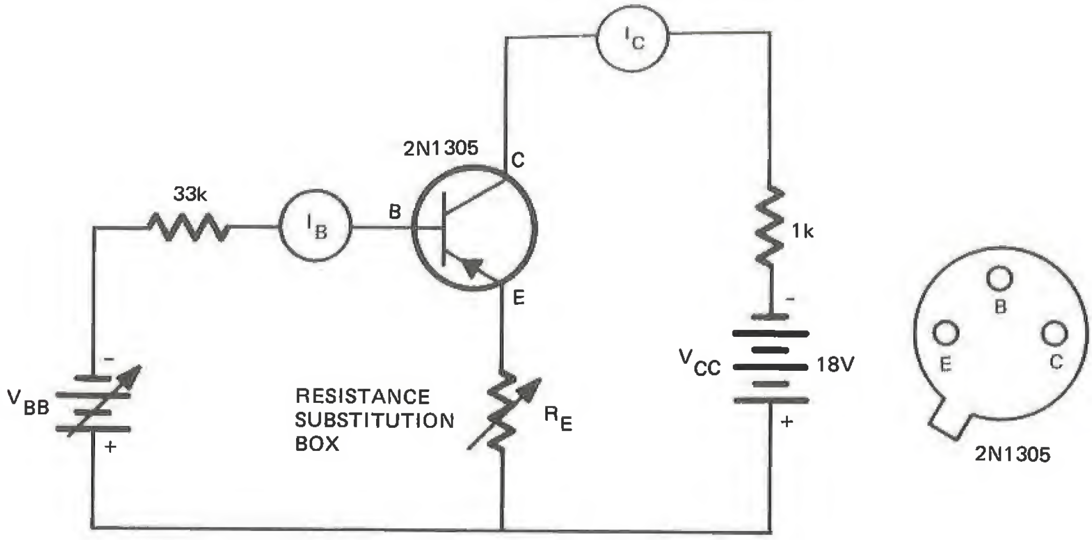


Fig. 8-7 The First Experimental Circuit

PROCEDURE

1. Assemble the circuit shown in figure 8-7.
2. Set R_E to zero ohms and the base current to 50 μA.
3. Allow the soldering iron to warm up.
4. Record the value of the collector current (I_C).
5. Compute and record the approximate value of α_F using $\alpha_F \approx -I_C/(I_C + I_B)$.
6. Hold the hot soldering iron near the top of the transistor case for about three to five seconds.
7. Record the maximum value reached by the collector current (I_C') as it increases due to the heat.
8. Allow the transistor to cool until the value of I_C returns to near the initial value measured in step 4.
9. Using the initial value of I_C and the maximum reached in step 7, compute and record the change in I_C (ΔI_C).
10. Using the value of α_F determined in step 5, and the values of R_B and R_E, compute and record the approximate value of the stability factor (S).
11. Repeat steps 4 and 6 through 10 for emitter resistor values of 470, 1000, 1500, 2200, 3300, and 4700 ohms. **Be sure to reset I_B to 50 μA before each temperature cycle.**
12. Assemble the circuit shown in figure 8-8.

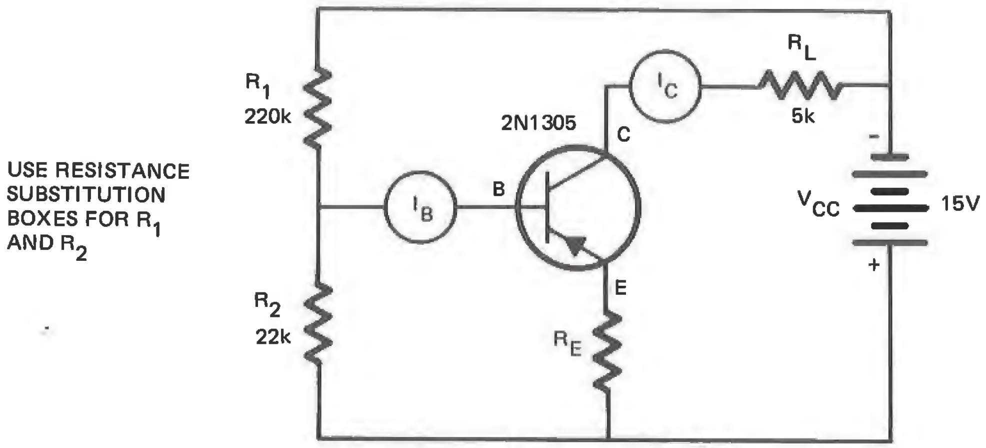


Fig. 8-8 The Second Experimental Circuit

13. Measure and record the values of I_B and I_C.
14. Compute and record the values of the equivalent V_{BB} and R_B.
15. As before, heat the transistor for three seconds and record ΔI_C.
16. Replace the R_1, R_2 bias network with the equivalent V_{BB} and R_B.
17. Again record I_B and I_C.
18. Heat the transistor as in step 15 and record ΔI_C.

ANALYSIS GUIDE. In the analysis of these data you should compare the values of the stability factors in the first circuit with the observed change in I_C. In the case of the second circuit, consider the extent to which the two bias networks appeared to give the same results.

R_E (ohms)	I_B (μA)	I_C (mA)	α_F	I'_C (mA)	ΔI_C (mA)	S
0						
470						
1000						
1500						
2200						
3300						
4700						

Data from First Experimental Circuit

Fig. 8-9 The Data Tables

Bias Circuit	I_B (μA)	I_C (mA)	V_{BB} (volts)	R_B (ohms)	ΔI_C (mA)
R_1, R_2 Network					
V_{BB}, R_B Network					

Data from Second Experimental Circuit

Fig. 8-9 The Data Tables (Cont'd)

PROBLEMS

1. What was the stability factor in the second experimental circuit?
2. Does the relationship of the stability factor to the change in collector current in the second circuit compare favorably with the trend in the first circuit?
3. If the quiescent collector current in a certain transistor is 5 mA and the stability factor is 12.6, what would be the new value of collector current if I_{CO} changes from 6 μA to 10 μA?

experiment 9 *TRANSISTOR AMPLIFIER GRAPHICAL ANALYSIS*

INTRODUCTION. The basic application of transistors is as electronic amplifying devices. In this experiment we shall examine the graphical method of analyzing a complete amplifier stage. Because the common emitter amplifier is the most frequently encountered type, it is the circuit that will be considered.

DISCUSSION. Let us consider the common emitter circuit shown in figure 9-1. To make the graphical analysis a little easier to handle, we can Thévenize the bias network in the base circuit by finding the equivalent bias battery (V_{BB}) and base resistance (R_B) using

$$V_{BB} = V_{CC} \frac{R_2}{R_1 + R_2} \quad \text{and}$$

$$R_B = \frac{R_1 R_2}{R_1 + R_2} \qquad \textbf{(9.1)}$$

And since we shall be initially concerned only with establishing the DC quiescent point, we may temporarily ignore the AC load (R and C_2) as well as the signal source (also the *coupling capacitor* (C_1) and the emitter *bypass capacitor* (C_3)). These changes are shown in figure 9-2.

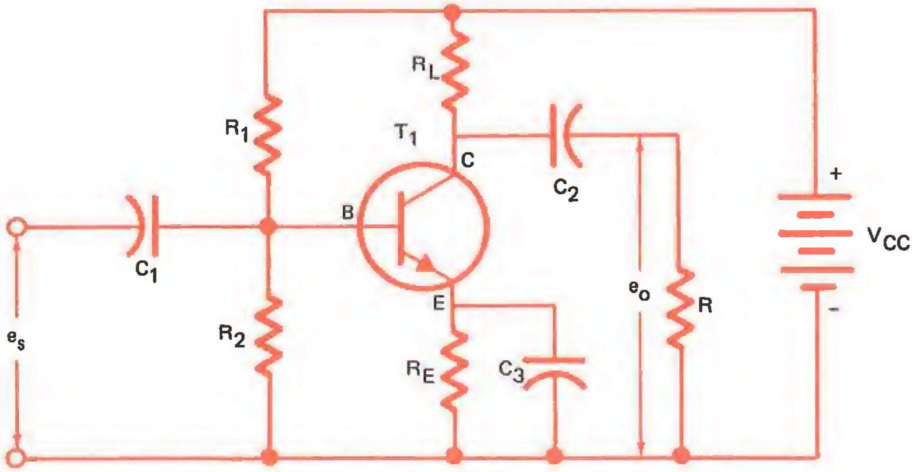


Fig. 9-1 A Practical Common Emitter Amplifier Circuit

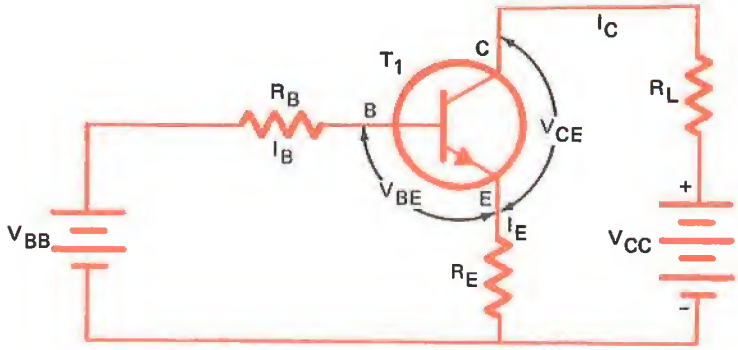


Fig. 9-2 The Simplified DC (Q-Point) Circuit

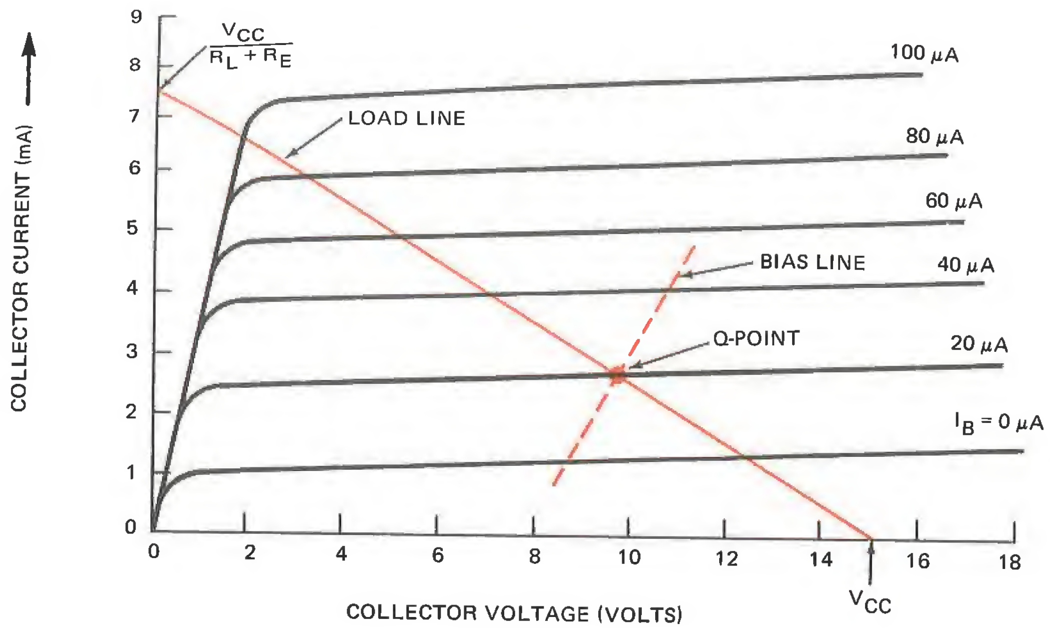


Fig. 9-3 A Typical Transistor Output Characteristic

The output characteristics of the transistor will be similar to those given in figure 9-3.

For purposes of illustration, let us suppose that the circuit component values are:

R_L = 1500 ohms	V_{CC} = 15 volts
R_E = 500 ohms	V_{BB} = 2 volts
R_B = 10k ohms	

Using these values we can construct the collector circuit loadline from V_{CC} on the collector voltage axis to

$$\frac{V_{CC}}{R_L + R_E} = \frac{15}{1500 + 500} = 7.5 \text{ mA}$$

on the collector current axis. Notice that this is the loadline of the series combination of R_L and R_E. The quiescent operating point must lie somewhere along this loadline.

To locate the exact Q-point, we must write the input and output loop equations

$$V_{BB} - I_B R_B - V_{BE} + I_E R_E = 0$$

and

$$V_{CC} - I_C R_L - V_{CE} + I_E R_E = 0$$

If we observe that $I_E + I_C + I_B = 0$ or $I_E = -I_C - I_B$, then we can reduce the loop equations to

$$V_{BB} - I_B(R_B + R_E) - I_C R_E - V_{BE} = 0$$

and

$$V_{CC} - I_B R_E - I_C(R_L + R_E) - V_{CE} = 0$$

Solving these two equations simultaneously and eliminating I_C we have

$$\boxed{V_{CE} = I_B\left[\frac{(R_B + R_E)(R_L + R_E)}{R_E} - R_E\right] + \left[V_{CC} - \frac{(R_L + R_E)(V_{BB} - V_{BE})}{R_E}\right]} \quad (9.2)$$

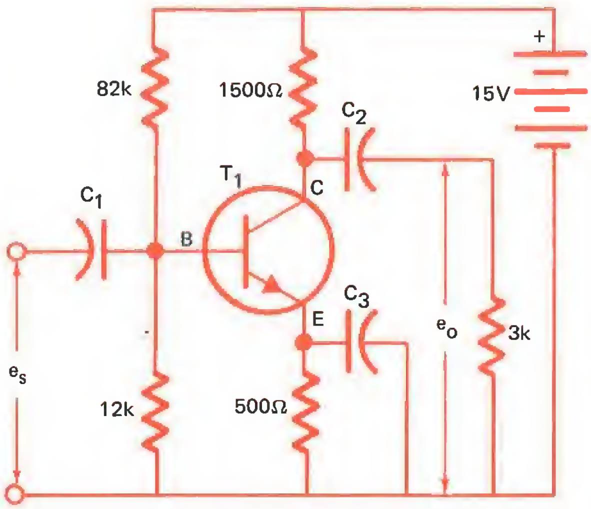


Fig. 9-4 The Example Circuit

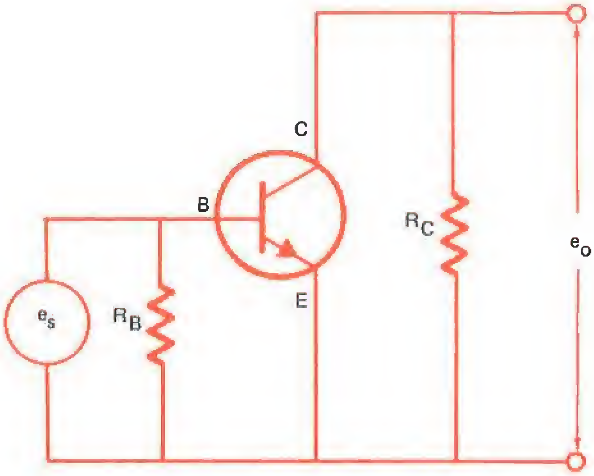


Fig. 9-5 The AC Equivalent Circuit

This equation, while being quite involved, reduces to a very useful form when the circuit values (and assuming 0.2 volts or 0.6 volts for V_{BE} of a germanium or silicon transistor, respectively) are used. For example, using V_{BE} = 0.2 volts and the component values given previously, it reduces to

$$V_{CE} = 42 \times 10^3 \, I_B + 7.8 \text{ volts}$$

Take particular note of the fact that this equation relates to the collector-emitter voltage (V_{CE}) to the base current (I_B) and may, therefore, be plotted on the output characteristics. The plot of this line (shown dotted in figure 9-3) is called the *emitter loadline* or the *bias line.*

The intersection of the bias line and the collector circuit loadline is the quiescent operating point of the transistor. In the example, we see that the Q-point is located such that the collector-emitter voltage (V_{CE}) is about 9 volts, the collector current (I_C) is about 3 mA, and the base current (I_B) is about 25 μA.

Having determined the DC operating conditions, let us now consider the signal (AC) conditions within the amplifier circuit. The original circuit is shown again in figure 9-4 with the component values used in the example above and assuming the following values:

R_1 = 82k ohms R = 3k ohms

R_2 = 12k ohms $e_s = 0.03 \sin \omega t$ volts

In a practical case, the reactance of the capacitors (C_1, C_2, and C_3) will be so small that they may be considered to be short circuits so far as the *AC* signal is concerned. Moreover, the battery internal AC resistance will be very near zero. Using these facts we may draw the *AC* equivalent circuit shown in figure 9-5. R_B is the same value as before, but now acts in parallel with the input resistance of the transistor. The total effective load in the collector circuit is the parallel combination of R_L and R. That is,

$$R_C = \frac{RR_L}{R + R_L} \qquad (9.3)$$

We must keep in mind the fact that the DC bias circuits not shown in the AC equivalent circuit are functioning to establish the quiescent operating point.

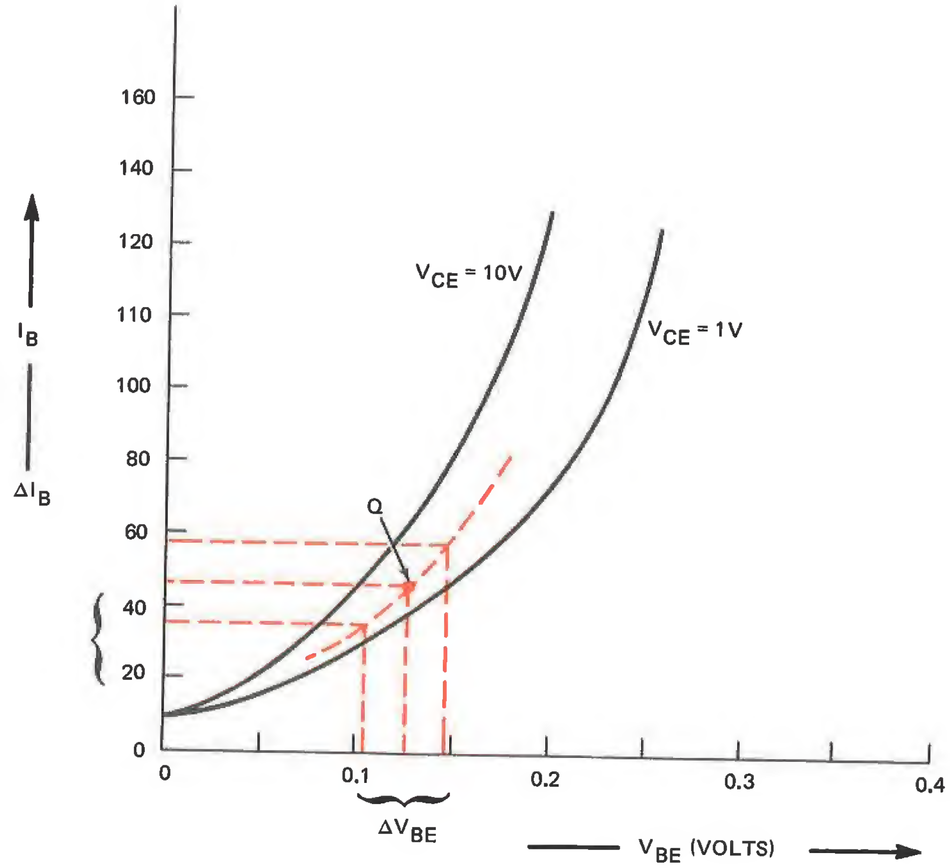


Fig. 9-6 A Typical Germanium Transistor Input Characteristic

The current from the input signal source divides between the equivalent base resistor and the dynamic input resistance of the transistor. Figure 9-6 shows a typical germanium transistor input characteristic. We may determine the approximate value of the transistor's dynamic input resistance (r_i) graphically using a small change in base current (ΔI_B) and the resulting change in base-to-emitter voltage (ΔV_{BE}):

$$r_i = \frac{\Delta V_{BE}}{\Delta I_B} \qquad \textbf{(9.4)}$$

and

$$r_i = \frac{V_{BE}}{I_B} \quad \text{at Q point} \qquad \textbf{(9.4A)}$$

In this case, $r_i \approx 0.04V/20\ \mu A = 2000$ ohms.

The AC input current to the stage will then be

$$i_B = \frac{e_s}{r_i} = \frac{0.03 \sin \omega t}{2000} = 15 \times 10^{-6} \sin \omega t \text{ amps}$$

In the collector circuit the operating point is still determined by the DC loadline, as indicated in figure 9-7. However, the AC signal has a load of

$$R_C = \frac{RR_L}{R + R_L} = \frac{3000 \times 1500}{4500} = 1000 \text{ ohms}$$

This load may be represented on the output characteristic as an AC *loadline*. We may construct this line by observing that it must pass through the quiescent point, Q, and have a

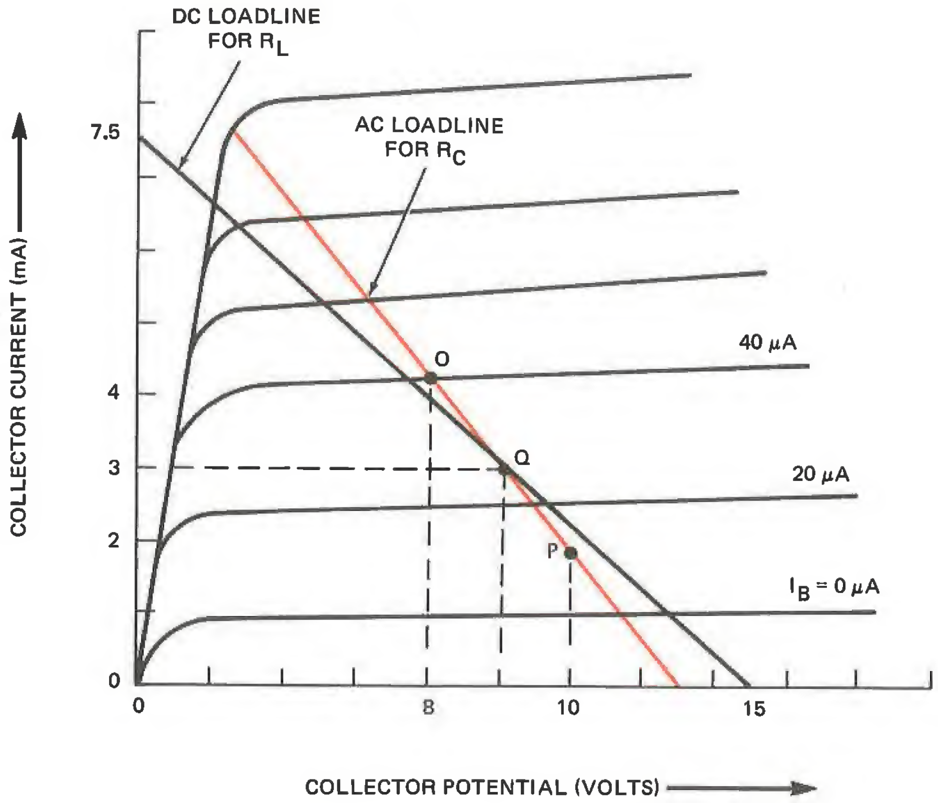


Fig. 9-7 Operation of the Common Emitter Amplifier

slope of $-1/R_C$. Since R_C is 1000 ohms, we see that, if V_{CE} changes 1 volts(from 9 volts to 10 volts), then I_C must change by

$$\Delta I_C = -\frac{\Delta V_{CE}}{R_C} = -\frac{1}{1000} = -1 \text{ mA}$$

which is from 3 mA (at Q) to 2 mA. If we plot the point P (on figure 9.7) at V_{CE} = 10 volts, I_C = 2 mA, we may draw the 1k AC loadline through P and Q. Notice that the AC loadline is not the same as the DC loadline.

Now, if we apply the AC base current ($i_B = 15 \times 10^{-6} \sin \omega t$) having a peak-to-peak amplitude of 30 μA, it will swing along the AC loadline from I_B = 10 μA (at point P) to I_B = 40 μA (at point O). And as a result, V_{CE} will swing from 10 volts to 8 volts. The AC component of the collector voltage will be 2 volts peak-to-peak and 180° out of phase with the AC base current. We may, therefore, write

$$e_o = -1 \sin \omega t \text{ volts}$$

At the same time, the collector current varies 2 mA peak-to-peak and is in phase with the AC base current; therefore,

$$i_c = 1 \times 10^{-3} \sin \omega t \text{ amps}$$

We may define the *voltage amplification* (or voltage gain) of the stage as

$$\boxed{A_v = \frac{e_o}{e_s}} \qquad (9.5)$$

In the example above, the voltage gain would be

$$A_v = \frac{e_o}{e_s} = \frac{-1 \sin \omega t}{0.03 \sin \omega t} \approx -67$$

which means that the AC output voltage is 67 times as large as the AC input voltage and is 180° out of phase with it.

We may also define the *current amplification* (or current gain) of the stage as

$$\boxed{A_i = \frac{i_L}{i_S}} \qquad (9.6)$$

where i_L is the current through the load resistor (R) and i_S is the total source current.

In our example we see that

$$i_L = -\frac{e_o}{R} = \frac{1 \sin \omega t}{3000}$$

$$= 0.67 \times 10^{-3} \sin \omega t \text{ amps}$$

The total source current will be

$$i_s = e_s / \frac{R_B r_i}{R_B + r_i} = 0.03 \sin \omega t / \frac{10{,}000 \times 2000}{12{,}000}$$

$$\approx 18 \times 10^{-6} \sin \omega t \text{ amps}$$

The current gain is, therefore,

$$A_i = \frac{i_L}{i_S} = \frac{0.67 \times 10^{-3} \sin \omega t}{18 \times 10^{-6} \sin \omega t} \approx 41$$

Finally, we can define the *power amplification* (or power gain) of the stage as

$$\boxed{A_p = |A_v||A_i|} \qquad (9.7)$$

which, in this case, would be

$$A_p = 67 \times 41 \approx 2750$$

In conclusion, we have seen that the graphic characteristics of a transistor may be used to determine both the DC and AC operating conditions.

MATERIALS

1 Transistor type 2N1304 or equivalent
1 Variable DC supply (0 - 40V)
1 VOM or FEM
1 Oscilloscope
1 Audio generator
1 Set of curves for 2N1304 transistor
3 10 μF, 50W VDC capacitors
1 1k ohm resistor 1/2W
1 1 meg resistor 1/2 W
1 8.2k resistor 1/2W
2 2.2k resistors 1/2W
1 33k resistor 1/2W
1 Transistor socket

PROCEDURE

1. On the transistor output characteristic plot the DC loadline for the circuit shown in figure 9-8.

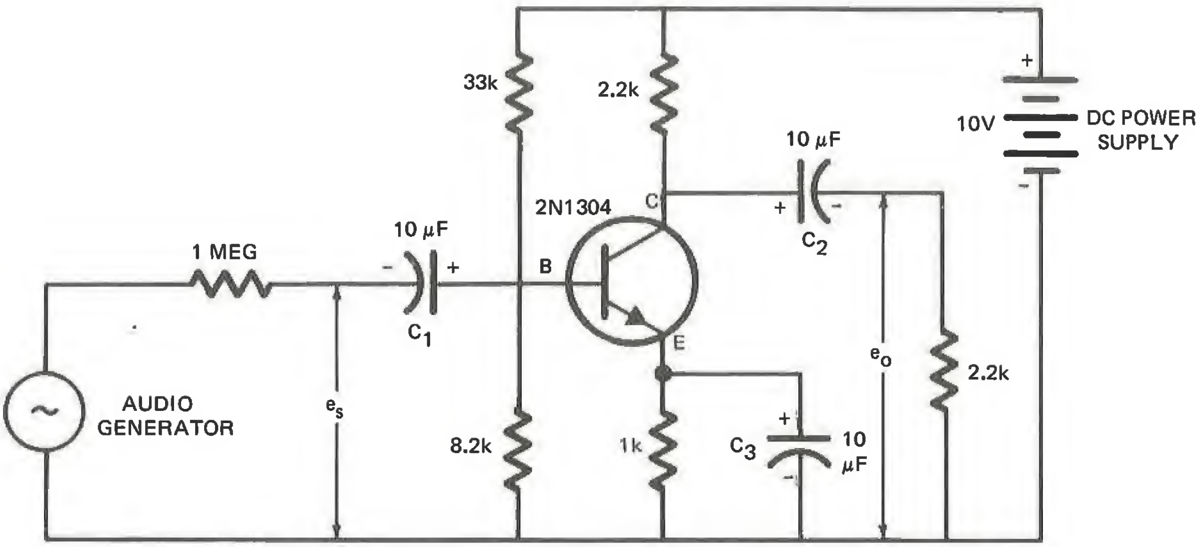


Fig. 9-8 The Experimental Circuit

2. Simplify equation 9.2 using the circuit component values specified in figure 9-8.
3. Plot the bias line on the output characteristics and locate the Q-point. Record the values of V_{CE}, I_C, and I_B at the Q-point.
4. Plot the AC loadline on the output characteristics of the transistor.
5. Locate the Q-point on the transistor's input characteristics and record V_{BE} and r_i.
6. Compute and record the input resistance of the stage (Z_i).
7. Compute and record the AC base current (i_B) and the AC source current (i_S) which will result if e_s is 10 mV rms.
8. Mark the peak-to-peak swing of the base current on the AC loadline. Record the corresponding swing in collector voltage and collector current e_c and i_c).
9. Compute and record the rms values of e_o and i_L.
10. Compute and record the values of A_v, A_i, and A_p.
11. Construct the circuit shown in figure 9.8.

Qty.	V_{CE}	I_C	I_B	V_{BE}	r_i	Z_i	i_B	Ie_c	i_s	i_c	e_s	e_o	A_v	i_L	A_i	A_p
Loadline Values																
Measured Values																

Fig. 9-9 The Data Table

12. With the audio generator set for zero output voltage, measure and record the DC operating values of V_{CE}, V_{BE}, I_C and I_B.
13. Connect the oscilloscope to measure e_s. Adjust the audio generator frequency to 1 kHz. Set the generator output level for an e_s of 10 mV (rms). Make a sketch of the input waveform
14. Move the oscilloscope to the output of the stage and measure e_o. Record the value of e_o in rms volts. Make a sketch of the output waveform.
15. Using a VOM, measure the rms voltage across the resistor in series with the audio generator. Compute and record the input current i_s.
16. Using the measured value of e_o and the resistance of the load, compute and record the AC load current (i_L).
17. Using measured values only, compute and record A_v and A_i.
18. Using A_v and A_i from step 17, compute and record A_p.

ANALYSIS GUIDE. In analyzing this data, you should compare the loadline values to the measured ones and evaluate the effectiveness of the loadline analysis in predicting the circuit performance. In particular, discuss any areas in which you feel that the loadline analysis was completely inadequate.

PROBLEMS

1. What was the stability factor of the circuit used in this experiment?
2. What was the value of X_c for C_3 in the experiment (at 1 kHz)? How does this value compare to R_E? What is the purpose of this capacitor?
3. What is the function of C_1 and C_2 in the circuit? Could either one of them be omitted from *this* experiment without affecting the results?

experiment 10 VACUUM TUBE CHARACTERISTICS

INTRODUCTION. The *vacuum tube* was for many years the basic electronic device, and there are still some applications in which it is used. In this experiment, we shall examine the terminal characteristics of the two most common types of tubes.

DISCUSSION. The *triode* vacuum tube is constructed by inserting a helically wound *grid* wire between the cathode and plate of a thermionic high vacuum diode. Such an arrangement is shown schematically in figure 10-1.

If we consider the cathode action when there is no potential applied to either the grid or the plate electrodes, we see that the space charge is formed just as in the case of a vacuum diode. Now, if we apply a negative potential to the grid, then the negative charge on the grid tends to force the space charge back toward the cathode.

On the other hand, when we apply a positive potential to the plate, the electrons are attracted to it. Because the grid is much closer to the space charge than the plate is, the grid has the greater influence of the two. The grid is consequently able to control the amount of plate current that flows for a given value of plate voltage. For this reason we call this element a *control grid.*

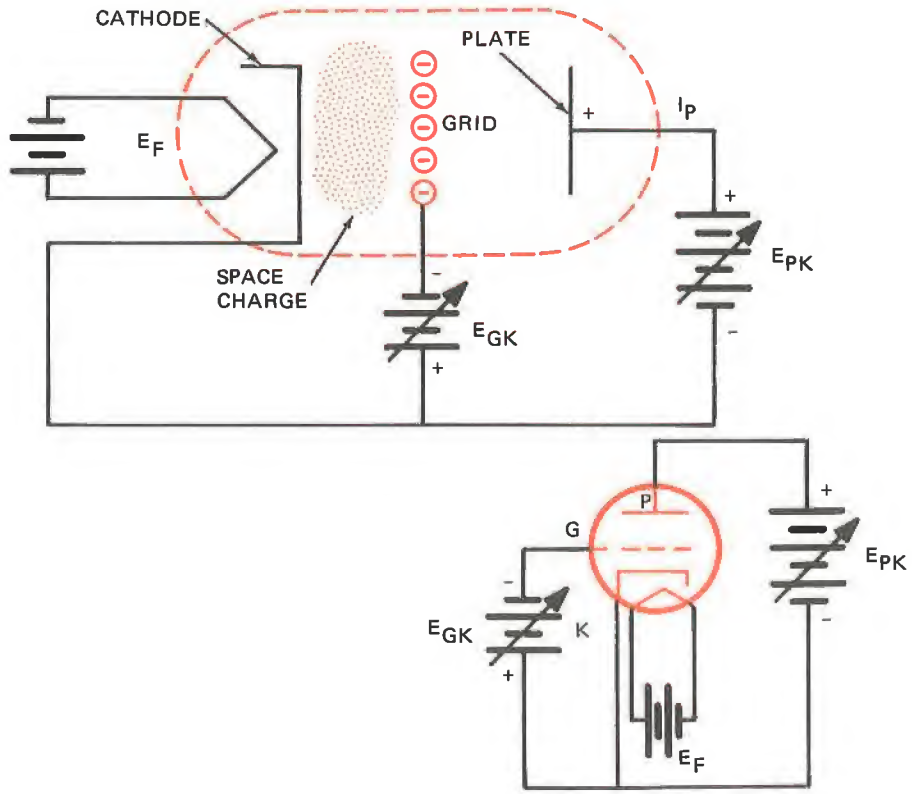


Fig. 10-1 A Triode Vacuum Tube

If the grid-to-cathode voltage (E_{GK}) is zero, then the amount of plate current that will flow (I'_P) will be

$$I'_P = \frac{E_{PK}}{R_P}$$

where R_P is effective static plate resistance. If some value of grid voltage (E_{GK}) is now applied, the plate current will change by an amount (ΔI_P) which is proportional to the change (ΔE_{GK}) in grid voltage. The constant of proportionality is called the transconductance (g_m) of the tube. The change in plate current will, therefore, be

$$\Delta I_P = g_m \, \Delta \, E_{GK}$$

The total plate current will now be

$$I_P = \Delta \, I_P + I'_P$$

or

$$I_P = gm \, \Delta E_{GK} + \frac{E_{PK}}{R_P}$$

And since we started with $E_{GK} = 0$, then the value of ΔE_{GK} will be equal to E_{GK} itself. We may therefore write

$$\boxed{I_P = g_m \, E_{GK} + \frac{E_{PK}}{R_P}} \qquad \textbf{(10.1)}$$

as the equation for plate current in a triode under *static* conditions. If E_{GK} is constant, then I_P tends to vary directly with E_{PK}. However, since g_m and R_P are both somewhat nonlinear, the *plate current and plate voltage are not linearly related.*

If E_{GK} is held constant, then the E_{PK}, I_P characteristic is essentially that of a vacuum diode. Changing E_{GK} tends to shift the curve but does not alter its basic shape much. A typical triode characteristic is shown in figure 10-2.

Let us now turn our attention to the input (control grid) characteristic. If we apply

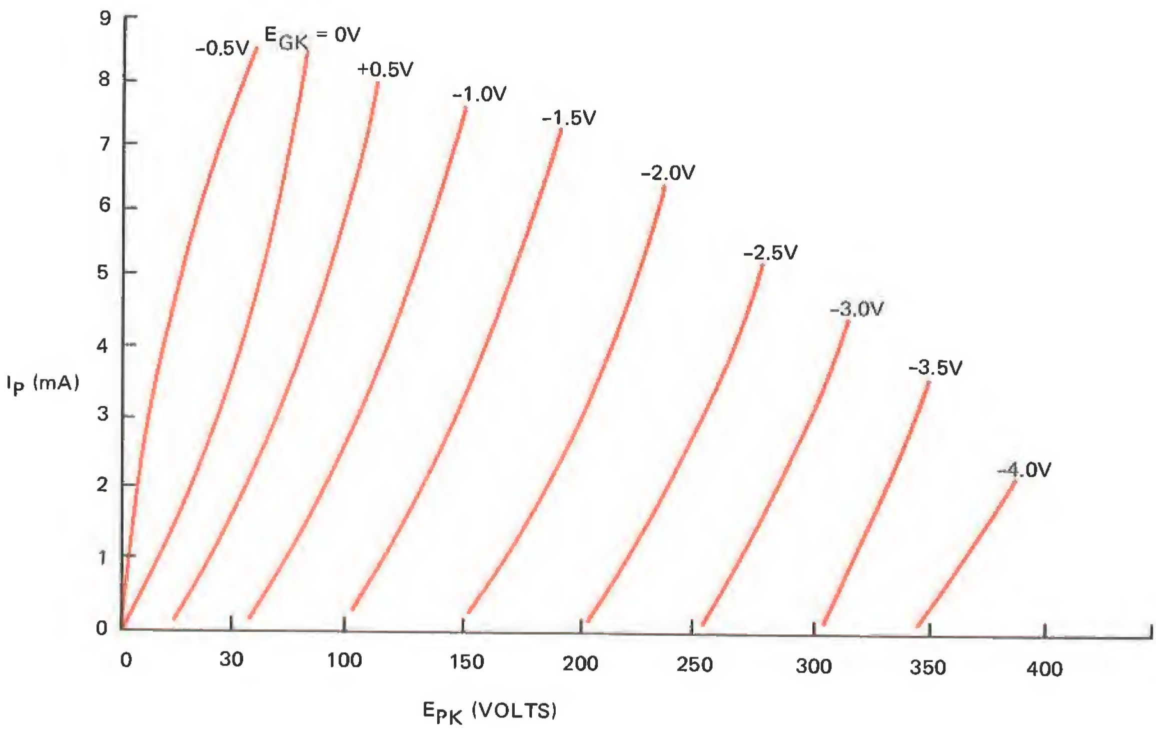


Fig. 10-2 A Typical Triode Output (Plate) Characteristic

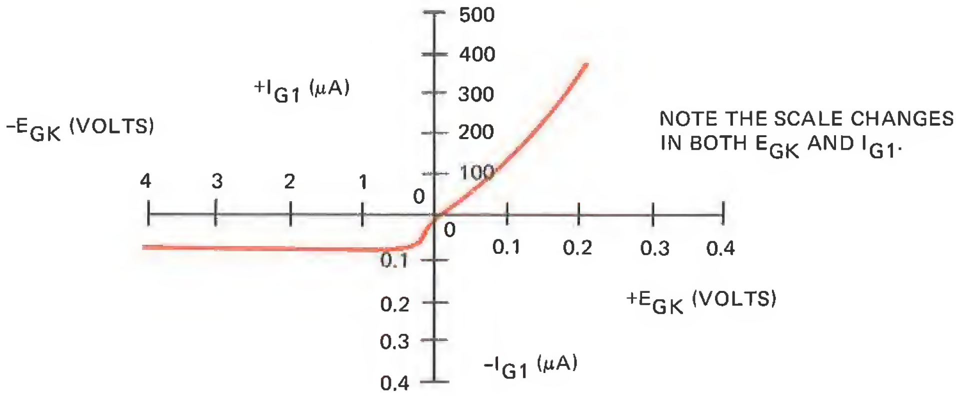


Fig. 10-3 A Typical Triode Input (Control Grid) Characteristic

a positive voltage to the grid, then it will draw current from the space charge and act just like a forward biased diode. On the other hand, if the grid voltage is negative, and plate current is flowing, an occasional electron will collide with the grid wires causing a very small reverse grid current (about 0.1 μA usually). Figure 10-3 shows a typical triode input characteristic.

Vacuum tubes, like transistors, may be connected in any one of three configurations. The most common arrangement (and the one considered in this experiment) is the common cathode circuit. The diagram of this configuration as well as those for the common plate and common grid circuits are shown in figure 10-4.

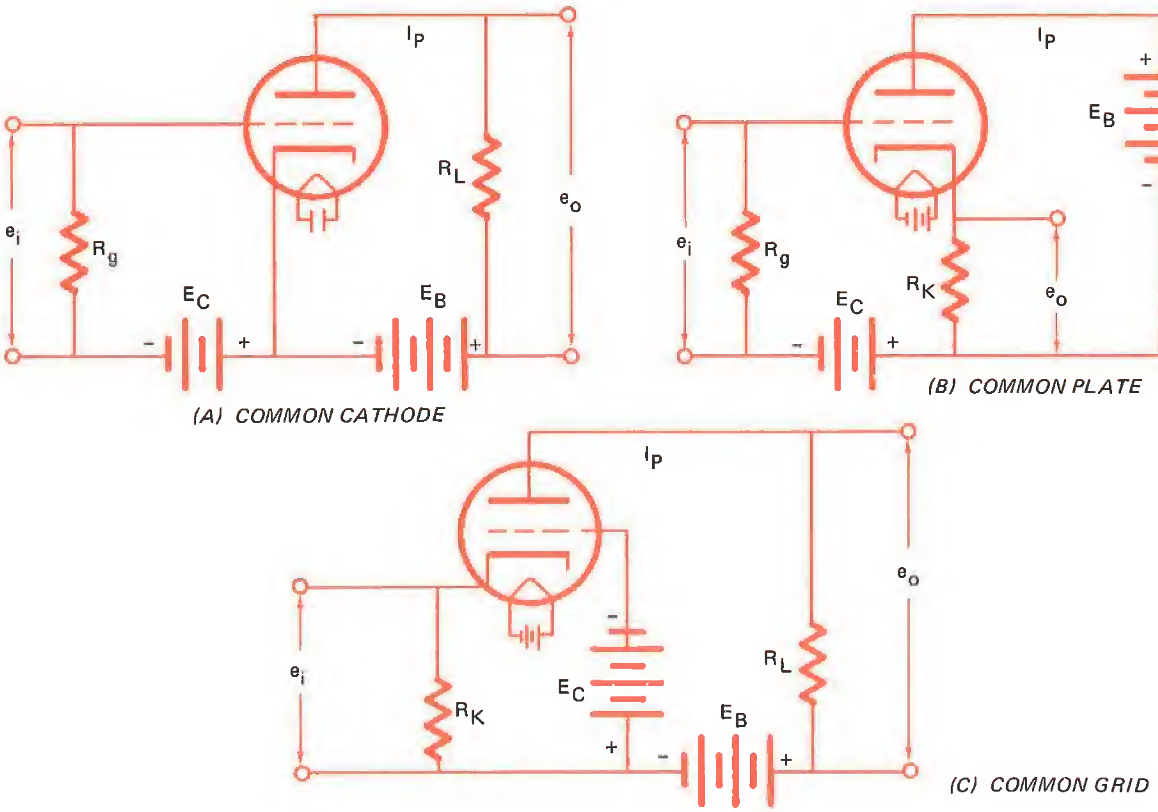


Fig. 10-4 The Three Vacuum Tube Circuit Configurations

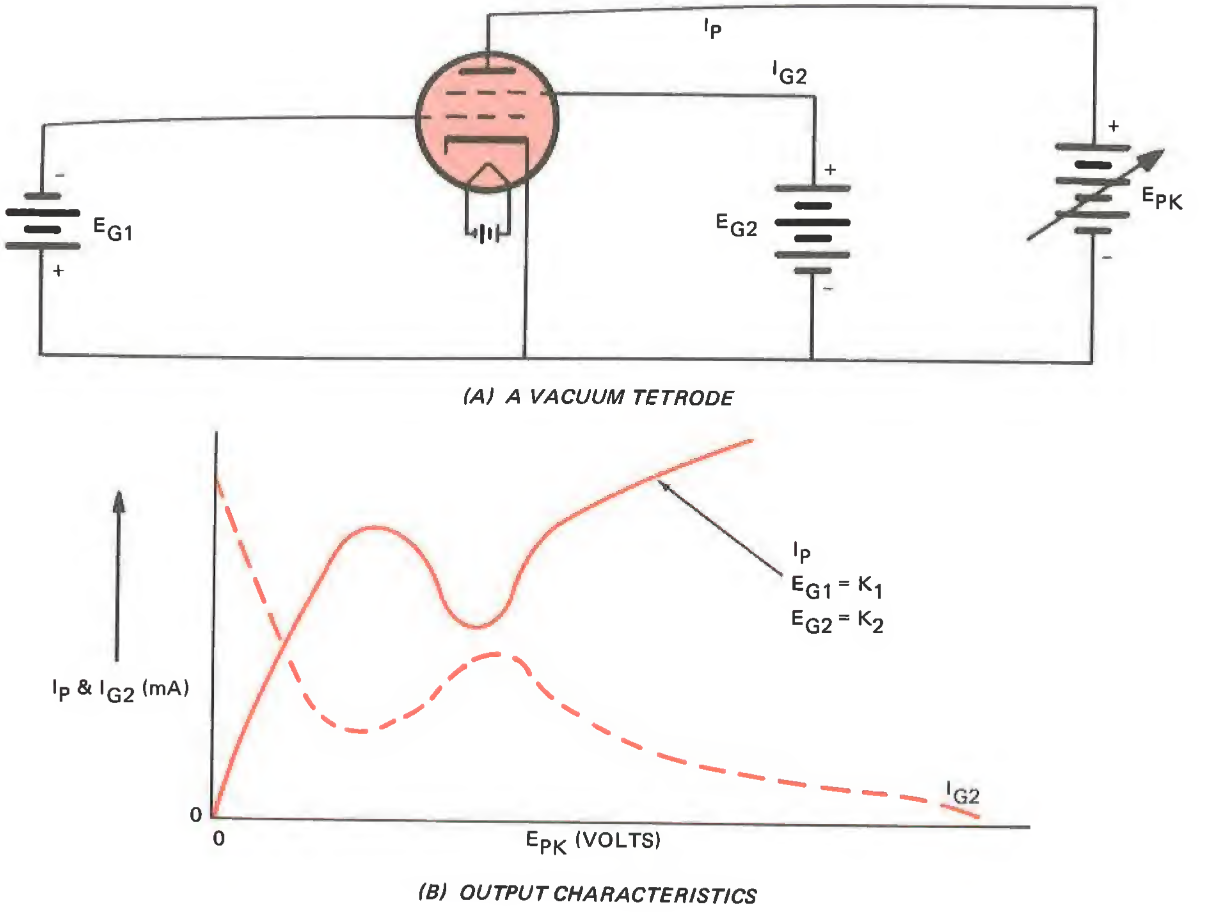


Fig. 10-5 A Vacuum Tetrode and its Output Characteristic

If we insert a second grid (called a screen grid) between the control grid and plate as shown in figure 10-5, the result is a four-element tube called a *tetrode.* Tetrodes were used for a while but were never very popular because of the severe dip in the plate current characteristic. The dip is caused by secondary emission of the plate current electrons.

Electrons leaving the space charge region are attracted toward the plate by the combined effect of the screen grid and the plate. At relatively low values of plate voltage, the electron velocities as they approach the plate are also low and the characteristics in this region are similar to those of a triode. As the plate voltage is increased, the electron velocities also increase until they reach a point where they strike the plate so vigorously that they literally knock other electrons loose from it. These *secondary emission* electrons are collected by the screen (grid) causing a dip in plate current and a rise in screen current as seen in figure 10-5(b).

As the plate potential is further increased, it becomes large enough to dominate the screen and the secondary electrons are attracted back to the plate as soon as they are knocked free.

To suppress the undesirable, secondary emission effects a third grid (called the *suppressor grid* G_3) is inserted between the screen

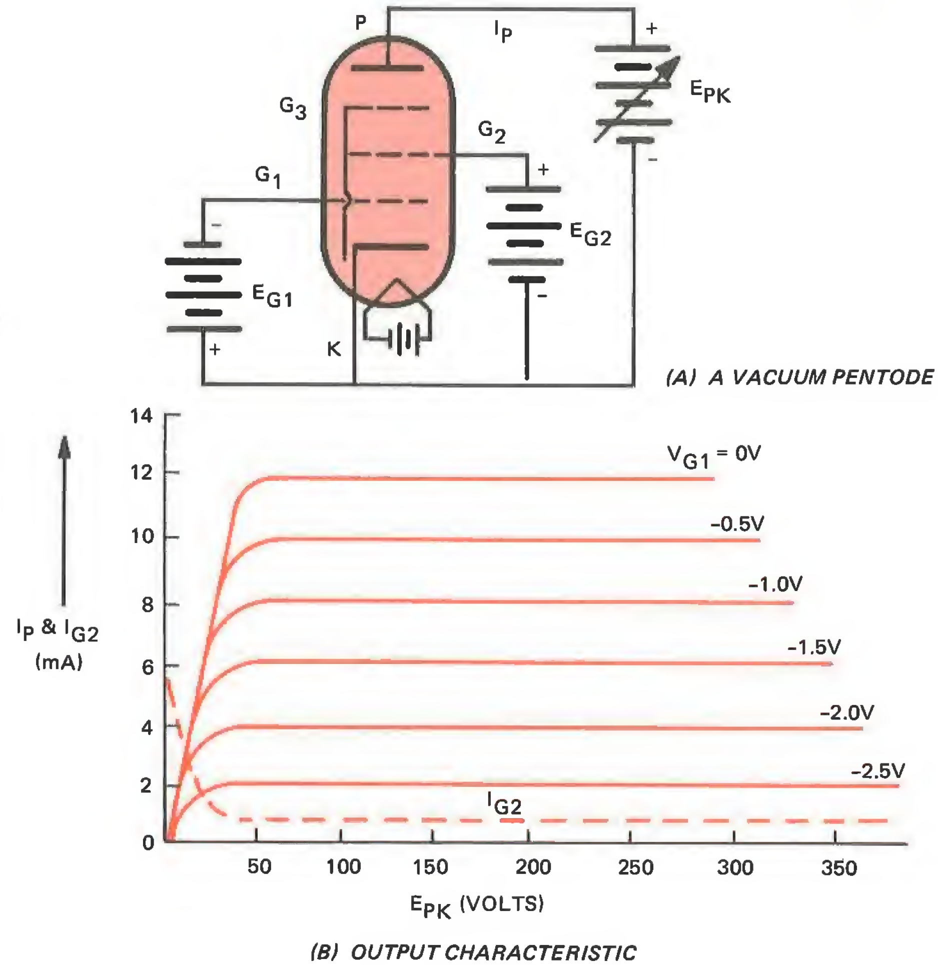


Fig. 10-6 A Vacuum Pentode and its Output Characteristic

grid (G_2) and the plate (P) as shown in figure 10-6(a). The five-element tube thus created is called a *pentode.*

This suppressor grid is tied electrically to the cathode (either inside the tube or externally) and is, therefore, at a potential level which is quite negative with respect to the plate. Secondary electrons seeing this relatively high negative potential are repelled back to the plate. There is, therefore, no dip in the typical pentode output characteristic shown in figure 10-6(b).

The input characteristic of a pentode is very much the same as that of a triode.

Both triode and pentode vacuum tubes are in common use today.

MATERIALS

1 High voltage, variable DC supply (0 - 400 volts) with separate bias supply (0 - 150 volts) and 6.3V filament supply
1 Low voltage, variable DC supply (0 - 40V)
2 VOMs or FEMs
1 Vacuum tube type 6AU8 or equivalent
1 9-pin miniature tube socket
1 10k ohm, 20W resistor
2 Sheets of linear graph paper

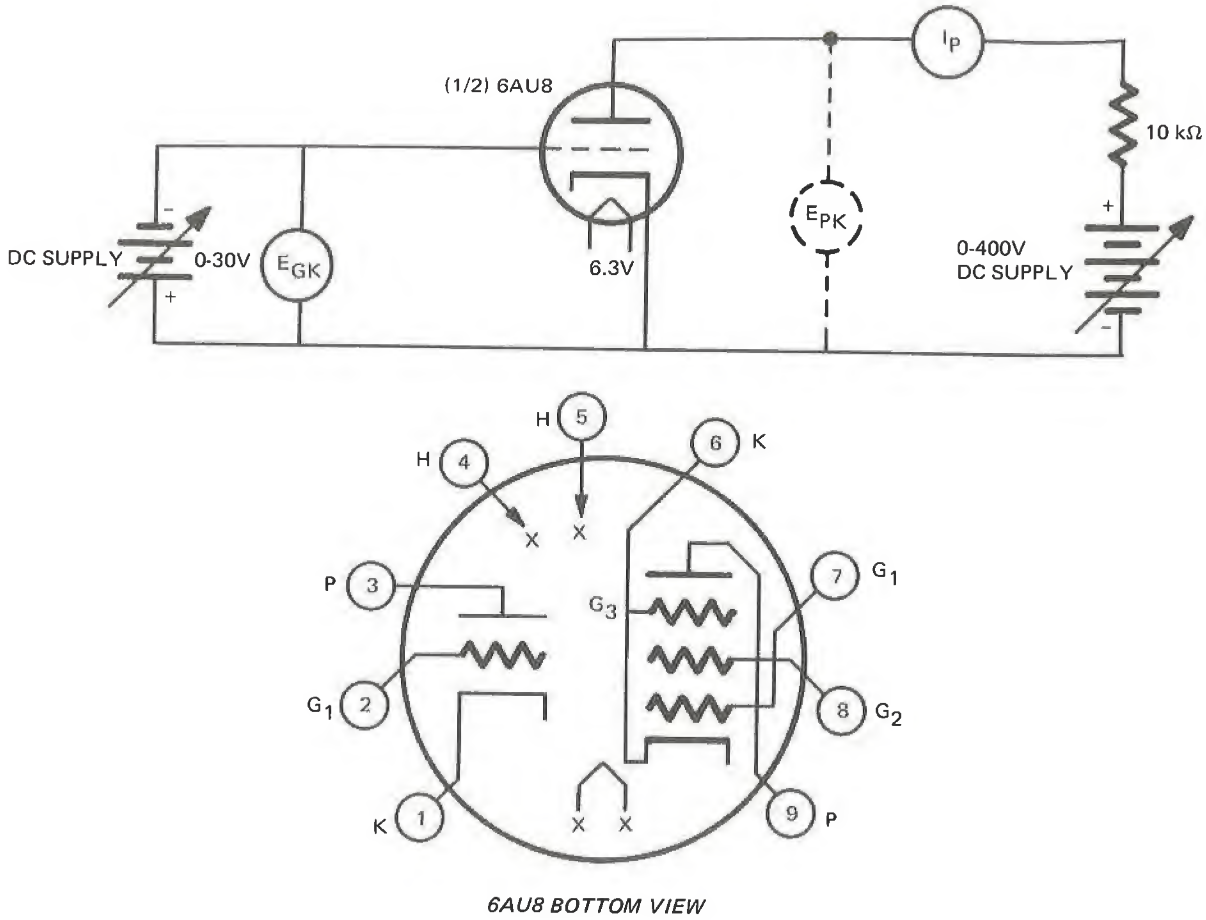
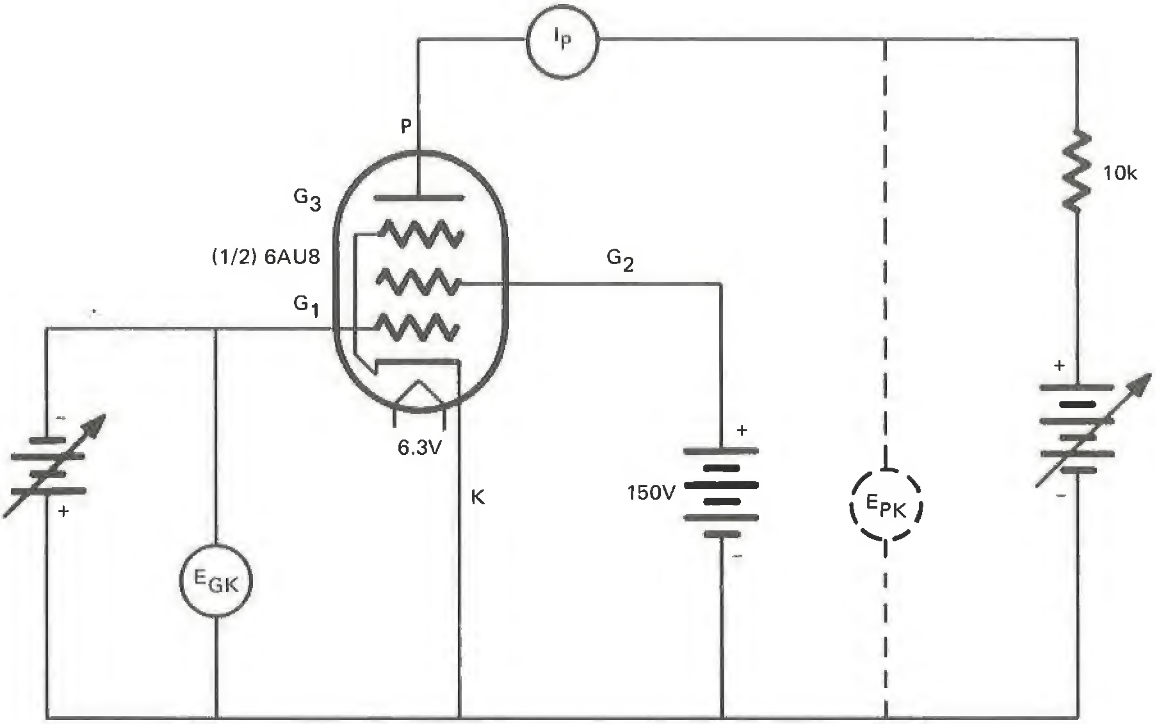
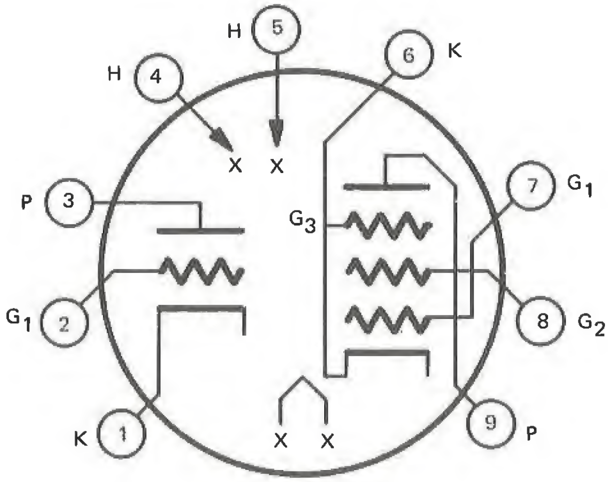


Fig. 10-7 The First Experimental Circuit

PROCEDURE

1. Assemble the circuit shown in figure 10-7. **Do not forget to connect the filament to the 6.3-volt power supply.**
2. Set the grid circuit supply for a grid-to-cathode voltage of –14.0 volts.
3. Measure and record the plate current (I_P) and plate voltage (E_{PK}) for plate voltage settings of 0, 50, 100, 150, 200, etc., up to the limit of variable plate supply.
4. Repeat steps 2 and 3 for grid voltages of –12.0, –10.0, -8.0, -6.0, -4.0, -2.0, 0.0, and +2.0.
5. Plot the output characteristic of the triode on a sheet of graph paper.
6. Disassemble the circuit given in figure 10-7 and assemble the one shown in figure 10-8. Use the bias supply output of the high voltage power supply for the screen grid voltage and be careful to connect all power supply polarities properly.
7. Set the grid voltage to –5.0 volts and the screen voltage to +150 volts.





6AU8 BOTTOM VIEW

Fig. 10-8 The Second Experimental Circuit

8. Measure and record the plate current (I_P) and plate voltage (E_{PK}) for plate voltage settings of 0, 50, 100, 150, 200, etc., up to the limit of the variable plate supply.

9. Repeat steps 7 and 8 for grid voltages of -4.0, -3.0, -2.0, -1.0, and 0.0 volts.

10. On a second sheet of graph paper, plot the output characteristic of the pentode.

E_{GK} (volts)	-14	-12	-10	-8	-6	-4	-2	0	+2
E_{PK} (volts)	I_P	I_P	I_P	I_P	I_P	I_P	I_P	I_P	I_P
0									
50									
100									
150									
200									
250									
300									
350									
400									

E_{GK} (volts)	-5	-4	-3	-2	-1	0
E_{PK} (volts)	I_P	I_P	I_P	I_P	I_P	I_P
0						
50						
100						
150						
200						
250						
300						
350						
400						

Fig. 10-9 The Data Tables

ANALYSIS GUIDE. In analyzing these data, you should examine your curves and compare them to the principles of operation of the tubes as explained in the discussion. In particular explain why the pentode curves do not look like diode characteristics whereas the triode curves do.

PROBLEMS

1. Compute the static resistance of each device at $E_{GK} = 0$ volts and $E_{PK} = 100$ volts.
2. Repeat problem 1 at $E_{GK} = 0$ volts and $E_{PK} = 200$ volts.
3. Discuss briefly the *trend* in R_P for each device using the values in problems 1 and 2.
4. Do a similar examination of the dynamic resistance (r_P) of the two devices.

INTRODUCTION. Some electronic devices (transistors) respond to variations in input current. These devices are biased by establishing a quiescent input current level. Other devices (*vacuum tubes,* for example) respond to variation in input voltage only and must, therefore, be biased by establishing quiescent input voltage level. In this experiment we shall consider ways of biasing voltage-actuated devices.

DISCUSSION. Let us review briefly the operation of a triode vacuum tube. The tube heater (or filament) warms the cathode which emits electrons charging the space nearby. The *space charge* electrons are attracted to the plate electrode by the applied plate potential. The *control grid* can effectively control the instantaneous plate current flow if it (the grid) is supplied with a negative bias voltage.

There are three different ways in which the negative grid bias may be supplied in a practical case. **The first, and perhaps most obvious way, is by using a separate bias voltage supply.** This method is shown in the circuit in figure 11-1. In this circuit the capacitors C_1 and C_2 function to couple the AC signal into and out of the stage. E_B is the plate voltage supply and R_L is the plate circuit load resistor. E_G is the grid bias supply which determines the level of the bias. The filament supply is not shown in the figure, but must, of course, be present in an operating circuit.

To determine the quiescent operating point of the tube, we use the output characteristics, as shown in figure 11-2.

For purposes of illustration, let us suppose that the circuit component values in figure 11-1 are:

E_B = 200 volts　　R_L = 33 k ohms

E_G = 3 volts　　R_G = 1 megohm

We may construct the DC plate circuit load-line from E_B on the plate voltage axis to $I_P = E_B/R_L$ = 6.06 mA on the plate current axis. The quiescent operating point of the

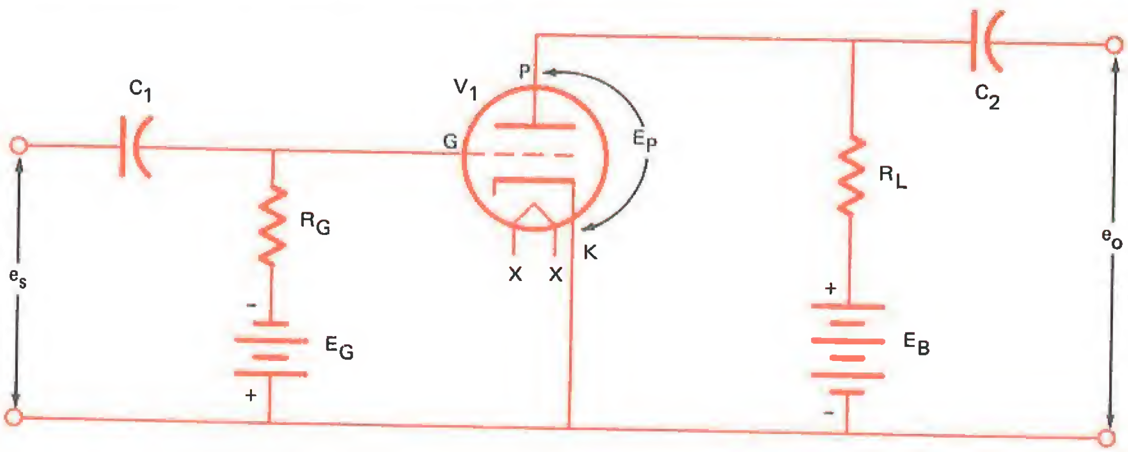


Fig. 11-1 Using a Separate Bias Supply

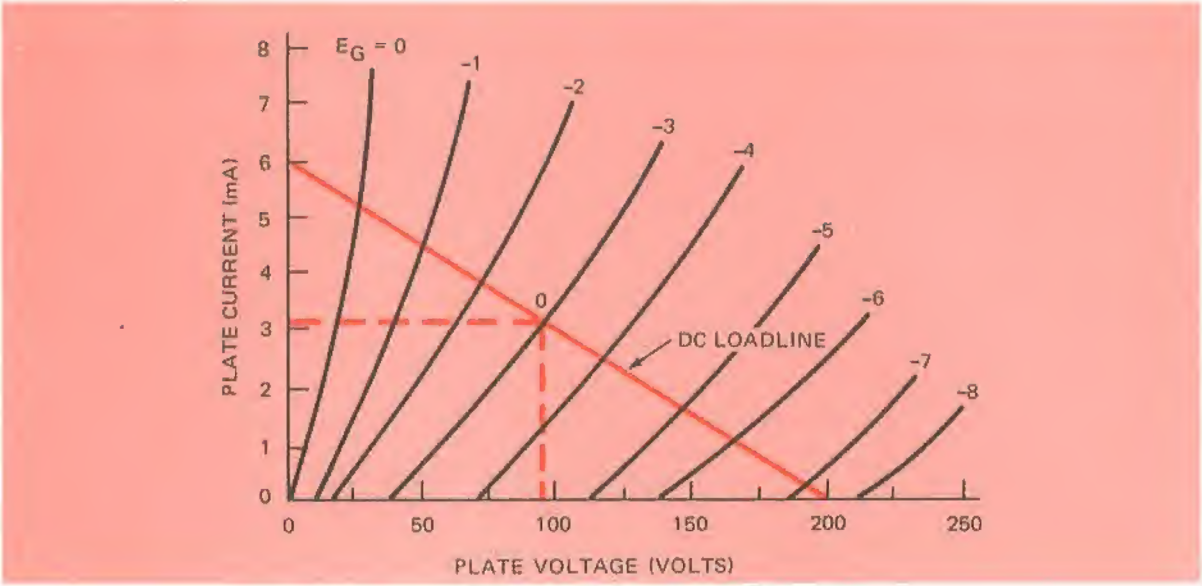


Fig. 11-2 A Typical Triode Output Characteristic

tube is located at the intersection of the DC loadline and the bias curve representing E_C (-3 volts). We see in figure 11-2 that the operating plate voltage would be about 100 volts while the quiescent plate current would be about 3.2 mA.

This separate supply method of biasing a tube is occasionally used in practice but only in very special cases.

A second method of biasing a tube is the grid leak method. As plate current flows in a tube, some electrons collide with the grid wires causing a grid current to flow. In most cases this *grid leakage current* is very small (frequently about 0.1 μA) but can be used to establish the *grid bias voltage.* Figure 11-3 shows a circuit using this type of bias. Because the grid current is quite small, a very large value of R_G is normally required to pro-

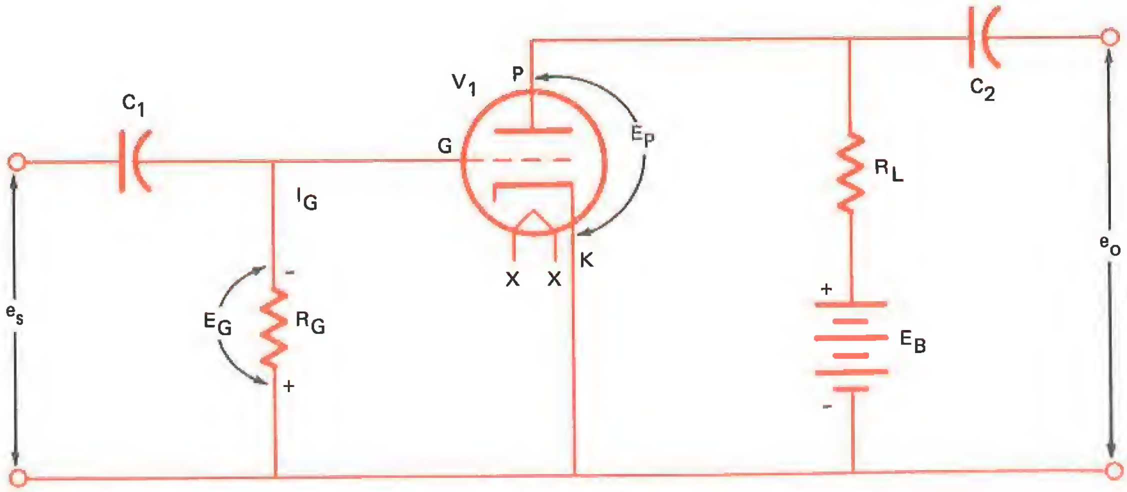


Fig. 11-3 A Triode Circuit With Grid Leak Bias

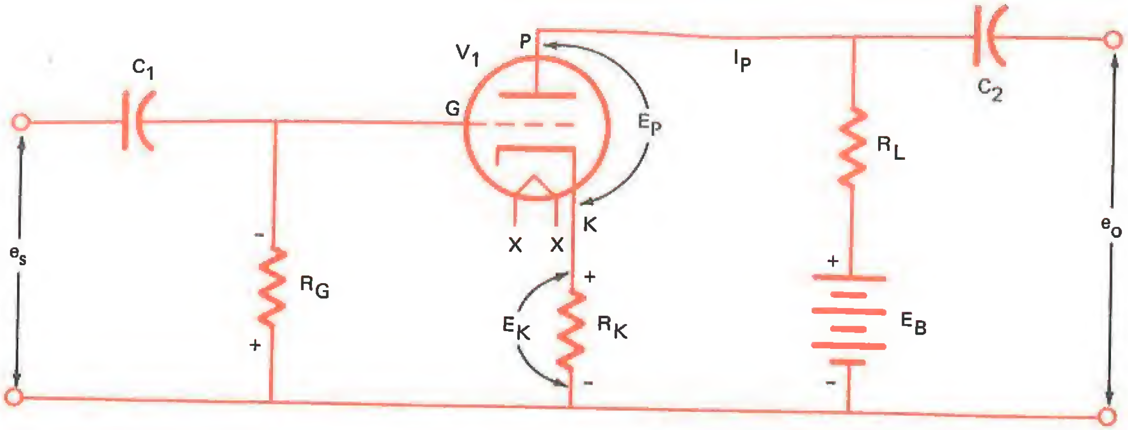


Fig. 11-4 A Triode Circuit With Cathode Bias

vide practical values. For example, if bias voltage is to be 3 volts and I_G is 0.1 μA, then R_G must be

$$R_G = \frac{E_G}{I_G} = \frac{3}{10^{-7}} = 30 \text{ megohms}$$

As in the case of the separate bias supply, *grid leak bias* is used occasionally, but only in very special cases.

The third and possibly most common bias method is called cathode or self bias. In this method, plate circuit current flowing into the cathode electrode is used to produce the bias voltage. Such a circuit is shown in figure 11-4.

In this circuit, as in the previous ones, the grid bias may be defined as the DC grid-to-cathode voltage. If we write the input loop equation, we have

$$E_G = -I_G R_G - I_P R_K$$

And if R_G is not extremely large, then the $I_G R_G$ term may be ignored, giving us

$$\boxed{E_G = -I_P R_K} \qquad (11.1)$$

In most cases R_G will be about 1 megohm or less and can be ignored.

In analyzing a cathode-biased circuit, we draw the plate circuit DC loadline using $R_L + R_K$ (that is, the loadline which extends from $I_P = E_B/(R_L + R_K)$ to E_B), as shown in figure 11-5 (assuming a value of 1000 ohms for R_K). Then we plot equation 10.1 on the output characteristics by choosing values of E_G and solving for I_P. The results in this case are

$$I_P = -E_G/R_K$$

E_G (volts)	-2	-3	-4
I_P (mA)	2	3	4

These points are then plotted at O, Q, and P in figure 11-5. The intersection of this *bias line* and the plate circuit DC loadline is the Q-point of the circuit.

A pentode vacuum tube has characteristics only slightly different from those already

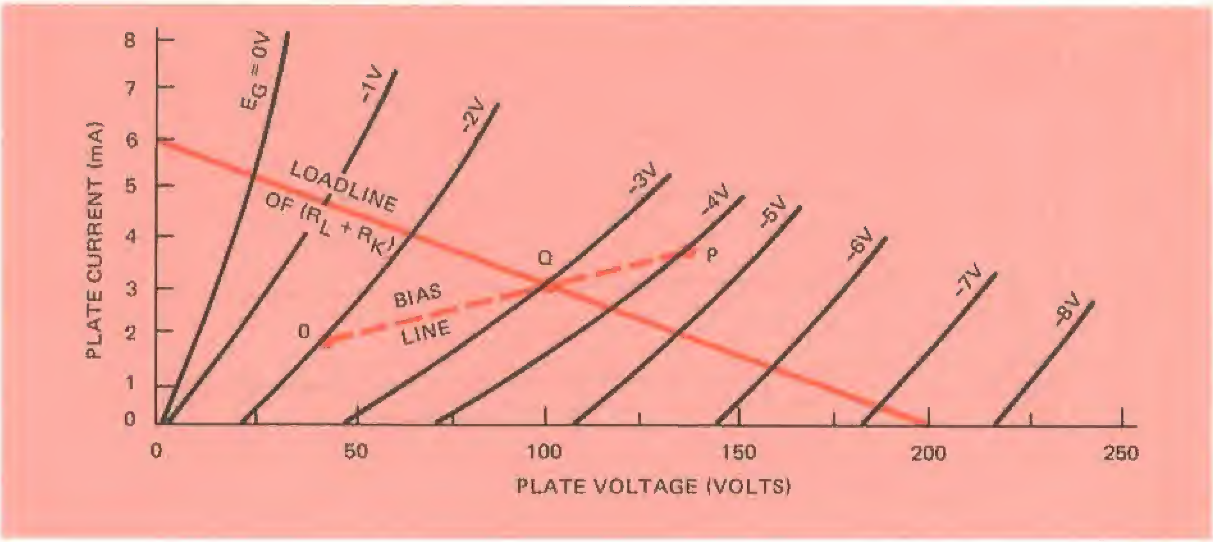


Fig. 11-5 Determining the Q-Point With Cathode Bias

discussed. Bias for a pentode may be established just as it is for a triode. In the case of a separate bias supply or grid leak bias, the analysis is identical to that of a triode. In the case of cathode bias, the analysis differs only because the pentode's screen grid current must be considered. Figure 11-6 shows a typical pentode circuit.

The resistors R_1 and R_2 are a voltage divider used to establish the screen voltage

$$\boxed{E_{G2} = E_B \frac{R_2}{R_1 + R_2}} \qquad (11.2)$$

The capacitor C_3 is the screen *bypass capacitor* used to hold the screen voltage constant.

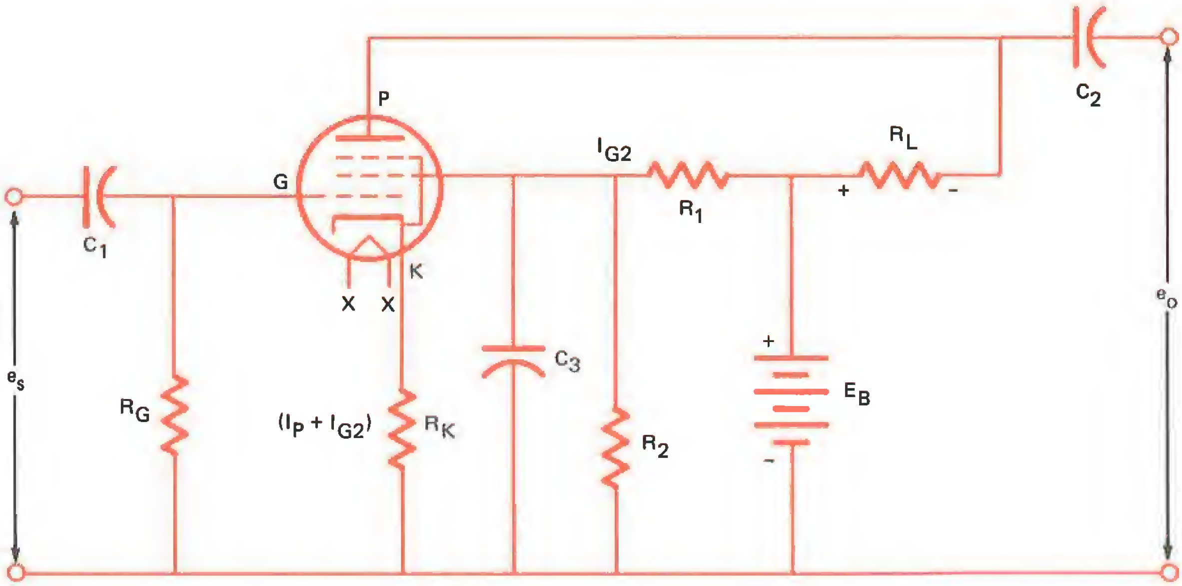


Fig. 11-6 A Pentode Circuit With Cathode Bias

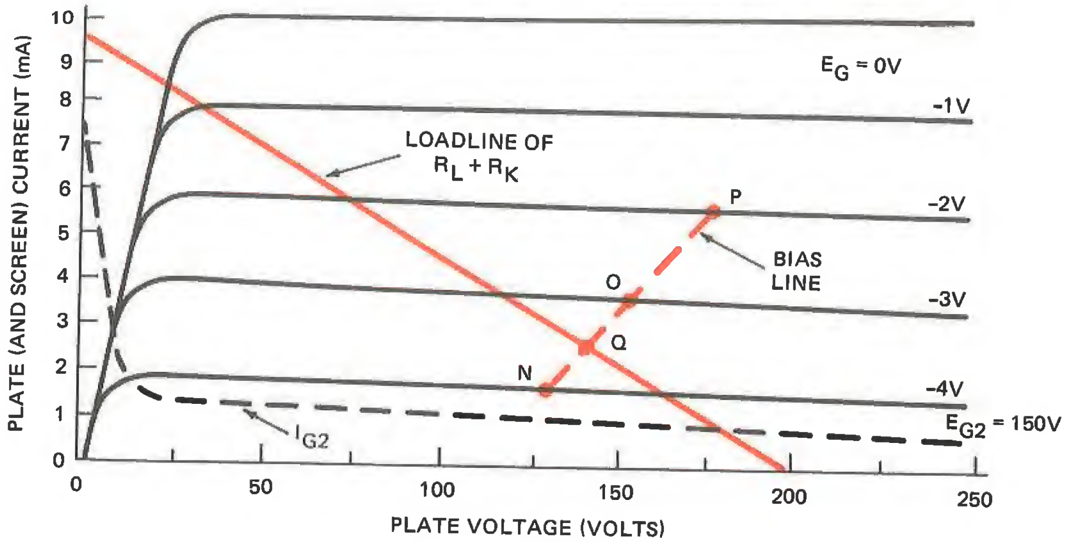


Fig. 11-7 Locating the Q-Point of a Pentode

The output characteristics of the pentode will be similar to those shown in figure 11-7.

In analyzing a pentode circuit, we first draw the plate circuit loadline using R_L and R_K as before. In this example let us suppose that the circuit values are:

R_L = 20 k ohms	R_1 = 5 k ohms
R_K = 740 ohms	R_2 = 15 k ohms
R_G = 470 k ohms	E_B = 200 volts

The loadline will extend from E_B = 200 volts to $I_B \approx 9.6$ mA as shown. To plot the bias line, we observe that the bias voltage is

$$E_G = -I_K R_K \qquad (11.5)$$

And the plate circuit loop equation is

$$E_B - I_P R_L - E_{PK} - I_K R_K = 0 \qquad (11.6)$$

Finally, we notice that the cathode current can be described by

$$I_K = I_P + I_{G2} \qquad (11.7)$$

Combining these three equations and solving for E_{PK} renders

$$E_{PK} = E_B + I_{G2} R_L + E_G \left(\frac{R_L}{R_K} + 1\right) \qquad (11.8)$$

Using the circuit values and equation 11.2, we see that the screen voltage is 150 volts. From the output characteristic we observe that I_{G2} is relatively constant at 1.5 mA over the linear portion of the curves. Using this value (I_{G2} = 1.5 mA) and the circuit components, we can reduce equation 11.6 to

$$E_{PK} = 230 + 28\, E_G$$

Choosing values of –2, –3, and –4 volts for E_G gives

E_G (volts)	-2	-3	-4
E_{PK} (volts)	174	146	118

Plotting these values at points N, O, and P on the output characteristic, we see that the Q-point is located at $E_{PK} \approx 135$ volts, $I_P \approx$ 3.2 mA, and $E_G \approx -3.5$ volts.

MATERIALS

1 18 k ohm resistor 2W
1 6AU8 vacuum tube or equivalent
1 9-pin tube socket
1 150-ohm resistor 2W
1 Variable DC power supply (0-400V)
1 Variable DC power supply (0-40V)
2 VOMs or FEMs
2 10 k ohm resistor 2W
1 Set of curves for 6AU8 tube
1 1-megohm resistor

PROCEDURE

1. Plot the DC loadline for the circuit shown in figure 11-8 on the output characteristics of the 6AU8 tube (triode section).

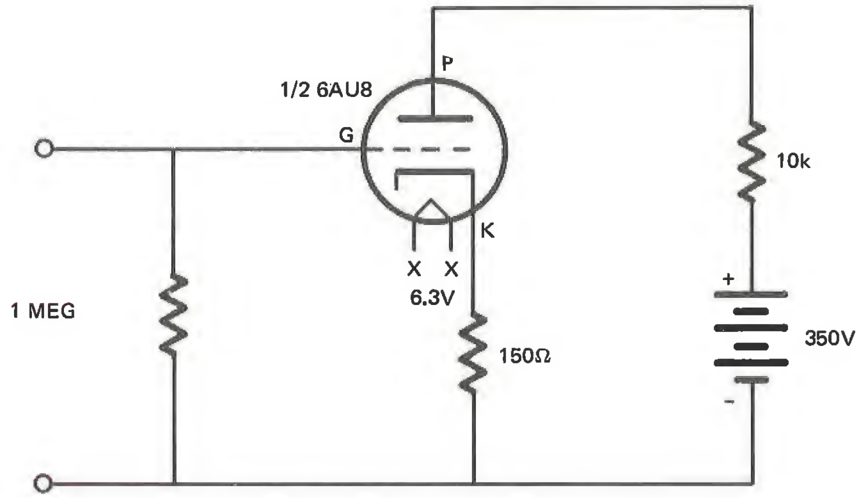


Fig. 11-8 The Triode Cathode Bias Circuit

2. Using equation 11.1 and the component values, plot the bias line on the triode output characteristics.
3. Locate the Q-point and record the values of E_P, I_P, and E_G.
4. Assemble the circuit and measure the quantities determined in step 3. Don't forget the filaments.
5. Remove the grid and cathode resistors from the circuit and reconnect the circuit as shown in figure 11-9.
6. Set the meter to the lowest DC voltage range. Record the reading as E_G.
7. With the meter reading and the resistance of the meter, compute and record the grid current (I_C).
8. Measure and record the values of E_P and I_P.
9. On the loadline used with the previous circuit, determine the value of E_G which corresponds to the values of E_P and I_P measured in step 8. Record this value as loadline data.

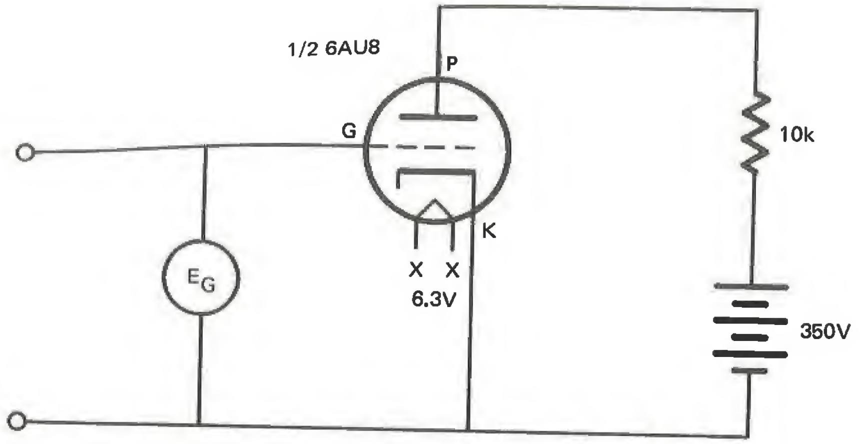


Fig. 11-9 The Triode Grid Leak Bias Circuit

10. Disassemble the triode circuit.
11. On the output characteristics of the pentode section of the 6AU8 tube, plot the DC load-line for the circuit shown in figure 11-10.
12. Compute and record the value of the screen grid voltage E_{G2}.
13. Using the I_{G2} curves on the output characteristics, estimate the value of I_{G2} near the middle of the range grid bias range. Record the value of your estimate in the data table.
14. Simplify equation 11.6 using the circuit component values and plot the bias line on the output characteristics.
15. Locate the Q-point and record the values of E_P, I_P, and E_{G1}.
16. Assemble the circuit shown in figure 11-10 and measure E_P, I_P, E_{G1}, E_{G2}, and I_{C2}. Record these values in the data table.

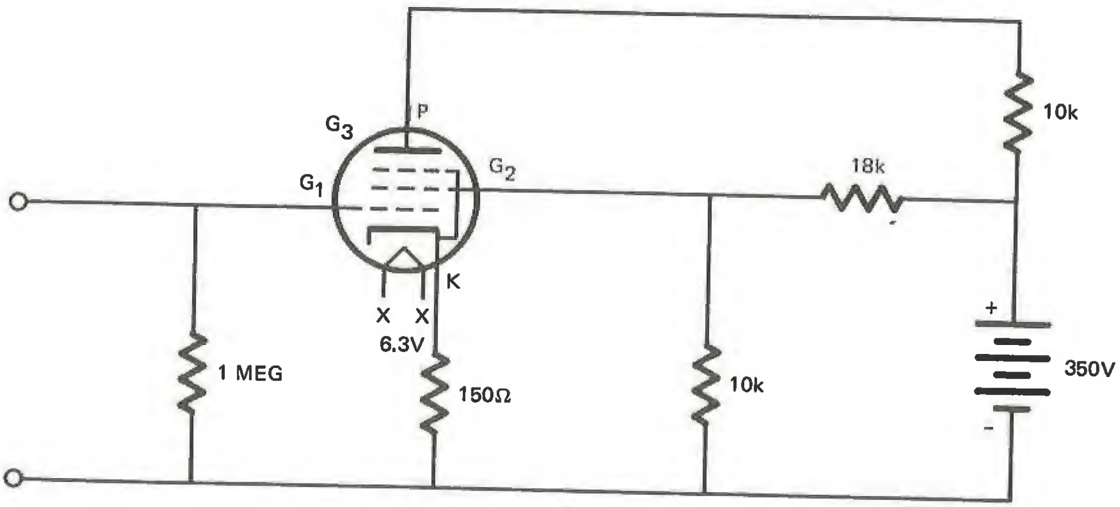


Fig. 11-10 The Pentode Experimental Circuit

Quantity	E_P	I_P	E_G
Loadline Data			
Measured Data			

Triode Cathode Bias Data

Quantity	E_P	I_P	E_G	I_G
Loadline Data	X	X		X
Measured Data				

Triode Grid Leak Bias Data

Quantity	E_{G2}	I_{G2}	E_P	I_P	E_{G1}
Loadline Data					
Measured Data					

Pentode Data

Fig. 11-11 The Data Tables

ANALYSIS GUIDE. The objective of this experiment has been to examine graphical methods of bias voltage analysis. In your analysis of the experimental data you should consider the extent to which the graphical analysis accurately predicted actual circuit performance.

Also, consider the extent to which the analyses of the bias circuits of the various devices were similar.

PROBLEMS

1. Would grid leak bias work as well with a pentode as with a triode? Explain your answer.
2. Why was it unnecessary to include screen grid and cathode bypass capacitors in this experiment?
3. What would be the bias on a triode if the cathode resistance was 1 k ohm and the plate current was 2.5 mA?

experiment 12 VACUUM TUBE AMPLIFIER GRAPHICAL ANALYSIS

INTRODUCTION. The basic application of a triode or pentode tube is as a voltage amplifier. In this experiment we shall examine graphical methods of determining the voltage gain and *power sensitivity* of a vacuum tube amplifier.

DISCUSSION. In analyzing the performance of a vacuum tube amplifier it is first necessary to establish the quiescent operating point. To this end, consider the circuit shown in figure 12-1. The loop equation for the DC plate current circuit will be

$$E_{BB} - I_P R_L - E_{PK} - I_P R_K = 0 \qquad (12.1)$$

which may be solved for I_P in the form

$$I_P = -\frac{E_{PK}}{R_L + R_K} + \frac{E_{BB}}{R_L + R_K}$$

This equation represents the DC loadline which may be plotted on the triode output characteristic from E_{BB} on the plate voltage axis to $I_P = E_{BB}/(R_L + R_K)$ on the plate current axis. If we have the following circuit values,

R_L = 10 k R = 10 k ohms

R_K = 270 ohms R_G = 1 megohm

E_{BB} = 300 volts e_s = 1 sin ωt volts

then the DC loadline will be as shown in figure 12-2.

If we write the grid-cathode loop equation assuming the grid current to be zero, we have

$$E_G + I_P R_K = 0 \qquad (12.2)$$

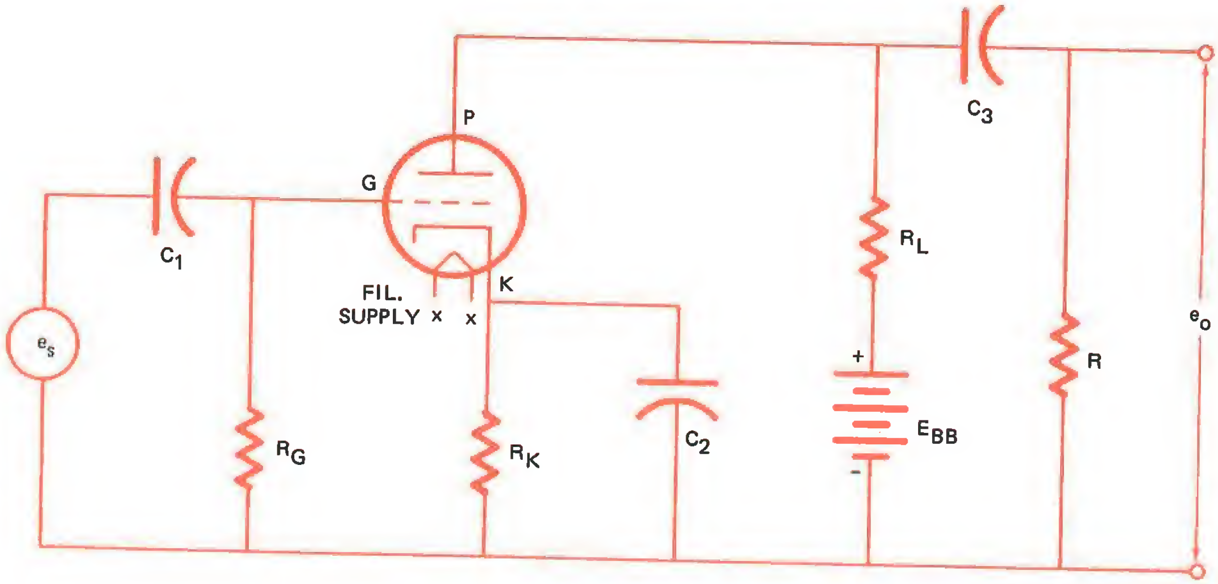


Fig. 12-1 A Typical Triode Amplifier

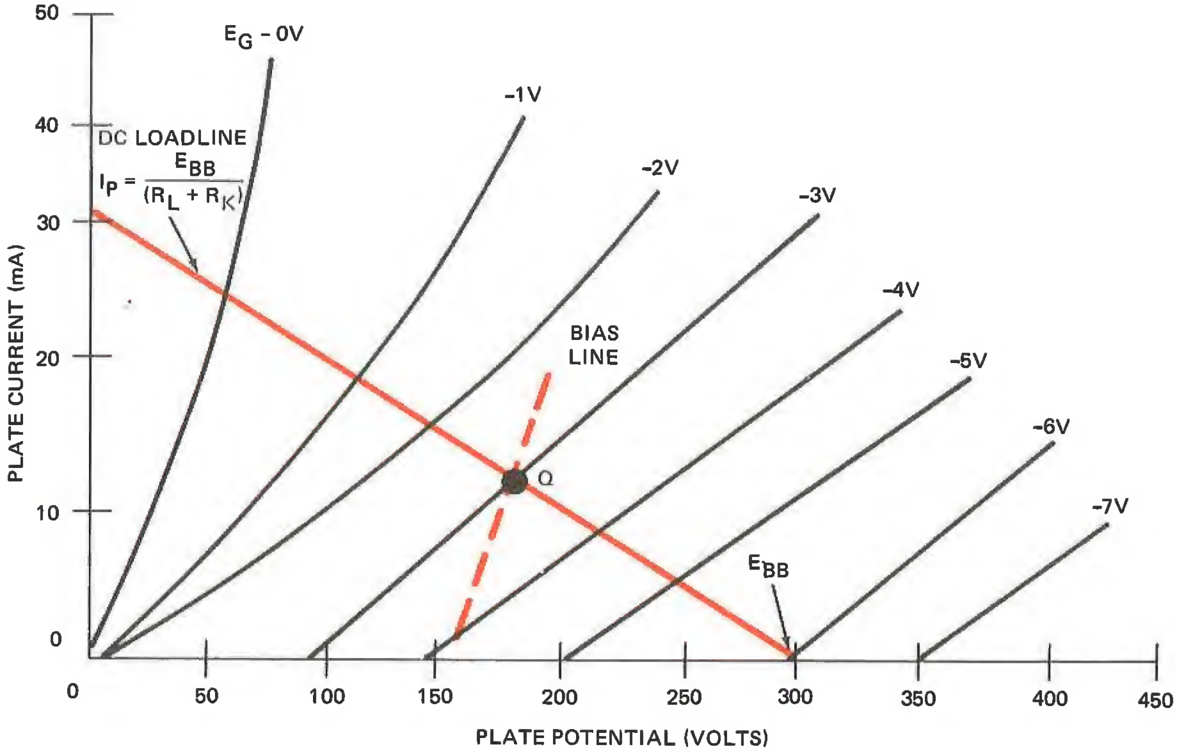


Fig. 12-2 Locating the Triode's Q-Point

Solving equation 12.1 and 12.2 simultaneously for E_{PK} renders

$$E_{PK} = E_{BB} + E_G\left(\frac{R_L}{R_K} + 1\right)$$

Using the circuit values specified, we can reduce this equation to

$$E_{PK} = 300 + 38\ E_G$$

Choosing appropriate values for E_C and evaluating E_{PK} gives us

E_G	-2.5V	-3.0V	-3.5V
E_{PK}	205V	186V	167V

These points are plotted as the bias line in figure 12-2. At the intersection of the DC load-line and the bias line we have the quiescent operating point and we observe that the quiescent point values are $E_{PK} \approx 185$ volts, $I_P \approx 1$ mA, and $E_G \approx -3$ volts.

The method of locating the Q-point used above was presented because it works well for several electronic devices (triodes, pentodes, transistors, FETs, etc.). In the special case of a triode vacuum tube, it is often more convenient to plot the bias line using only equation 12.2:

$$I_P = -\frac{E_G}{R_K}$$

E_G	-2.5V	-3.0V	-3.5V
I_P	9.26 mA	11.1 mA	13.0 mA

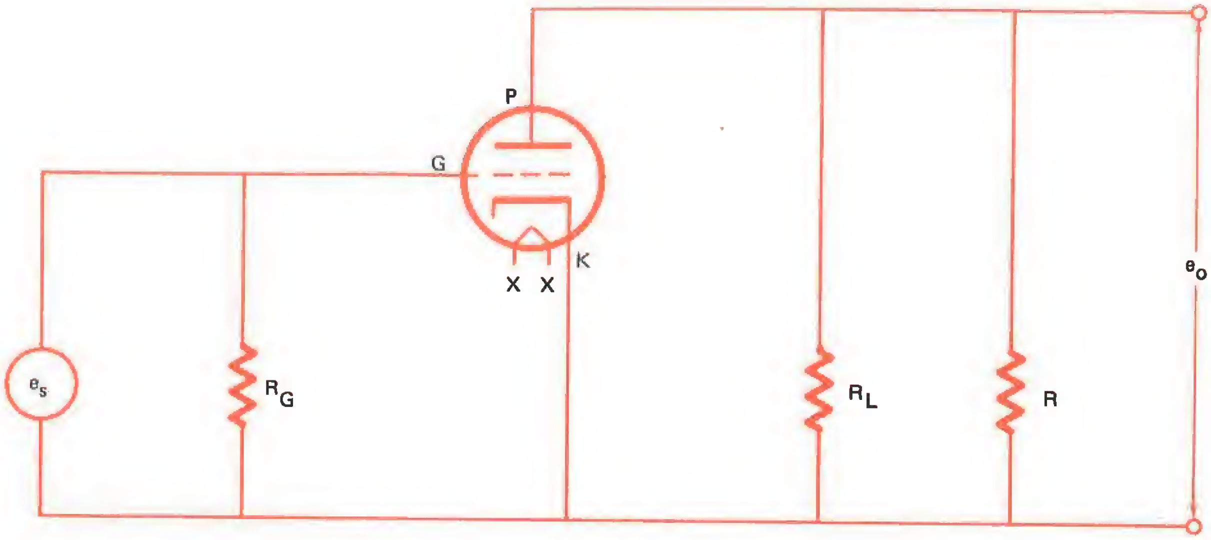


Fig. 12-3 The AC Equivalent Circuit

Using this method is quicker than the one described previously but is really only practical for the triode vacuum tube. Consequently, the previous, more involved method is most frequently encountered.

With the Q-point conditions established, we shall now consider the AC equivalent circuit. If the circuit capacitors and the plate voltage power supply have impedances that are low enough to be ignored, the AC equivalent will be as shown in figure 12-3. The total effective AC load resistance in the plate circuit will be the parallel equivalent of R_L and R,

$$R'_L = \frac{R_L R}{R_L + R} \qquad (12.3)$$

and the plate circuit loop equation becomes

$$E_{PK} + I_P R'_L = 0$$

or

$$I_P = \frac{-E_{PK}}{R'_L} \qquad (12.4)$$

This equation represents the AC loadline which passes through the Q-point and has a slope of $-1/R'_L$.

This loadline may be plotted on the output characteristic by choosing an appropriate change in plate voltage (ΔE_{PK}) and computing the resulting change in plate current (ΔI_P) using equation 12.4:

$$\Delta I_P = \frac{-\Delta E_{PK}}{R'_L}$$

If we let ΔE_{PK} = 50 volts, then

$$\Delta I_P = - \frac{50}{5 \times 10^3} = -10 \text{ mA}$$

using values of R_L and R given previously. Then starting at the Q-point, we move right 50 volts and down 10 mA to point P (see figure 12-4). The AC loadline may then be drawn passing through points P and Q.

With the AC loadline constructed we may determine the voltage gain of the ampli-

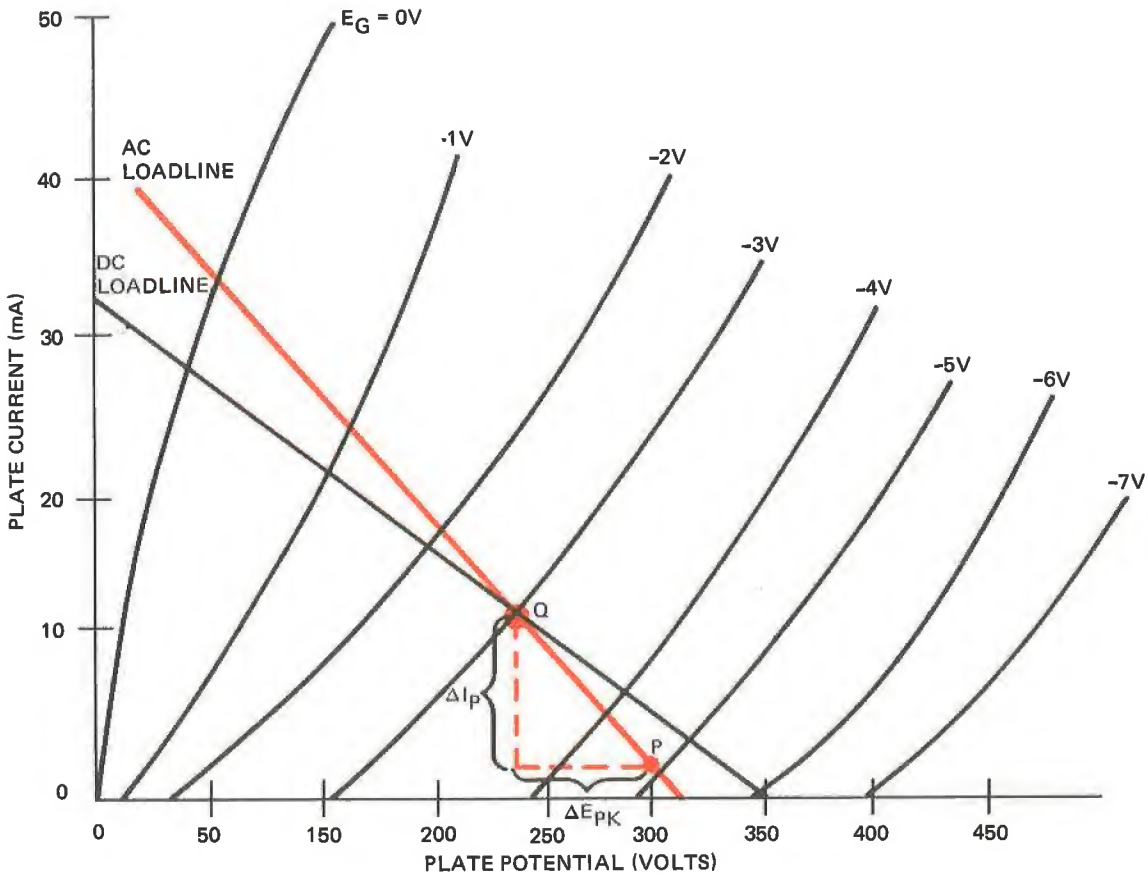


Fig. 12-4 Constructing the AC Loadline

fier. If the input AC signal ($e_s = 1 \sin \omega t$) swings two volts from peak-to-peak along the AC loadline from -2 volts to -4 volts, the plate voltage will swing from about 150 volts to about 230 volts. This is a total peak-to-peak swing of 80 volts and the voltage gain is

$$A_v = \frac{e_o}{e_s} = -\frac{80}{2} = -40$$

The negative sign indicates the phase reversal (the plate voltage goes positive as the grid voltage goes negative).

The power sensitivity of an amplifier is defined as the power output per rms input volts squared:

$$\boxed{\text{Power Sens} = \frac{P_o}{E_s^2}} \qquad (12.5)$$

Since the output power to the load is given by

$$P_o = \frac{E_o^2}{R}$$

we may write equation 12.5 as

$$\text{Power Sens} = \left(\frac{E_o^2}{E_s^2}\right)\frac{1}{R} = \frac{|A_v|^2}{R} \qquad (12.6)$$

Inspection of the original circuit will reveal that the input current depends only on the value of R_G (assuming the grid current to be zero). Therefore, we may vary the input current over a considerable range by choosing different values of R_G. Because of this situation, the current and power gains of a vacuum tube amplifier are usually of only casual interest. They can, however, be determined by

$$A_i = \frac{i_L}{i_s} = \frac{e_o/R}{e_s/R_G} = \left(\frac{e_o}{e_s}\right)\frac{R_G}{R} = A_v\left(\frac{R_G}{R}\right) \quad (12.7)$$

and

$$A_p = \frac{P_o}{P_i} = \frac{E_o^2/R}{E_s^2/R_G} = \left(\frac{E_o^2}{E_s^2}\right)\frac{R_G}{R} = |A_v|^2\left(\frac{R_G}{R}\right) \quad (12.8)$$

when desired.

The graphical analysis of a pentode tube amplifier is the same as that of a triode tube amplifier. However, the screen current in a pentode does flow through the cathode resistor and must, therefore, be considered in determining the Q-point.

MATERIALS

- 1 Vacuum tube type 6AU8 or equivalent
- 1 Set of triode and pentode characteristics for the tube
- 1 9-pin miniature tube socket
- 1 Variable DC power supply (0 - 400V)
- 1 VOM or FEM
- 1 Audio generator
- 1 Oscilloscope
- 1 10 μF 50W VDC capacitor
- 3 0.1 μF 600W VDC capacitors
- 1 560 ohm resistor 2W
- 1 20 k ohm resistor 2W
- 1 33 k ohm resistor 2W
- 1 320 k ohm resistor 2W
- 1 150 ohm resistor 2W
- 2 10 k ohm resistors 2W

PROCEDURE

1. Using the triode output characteristics, plot the DC loadline of the circuit shown in figure 12-5.

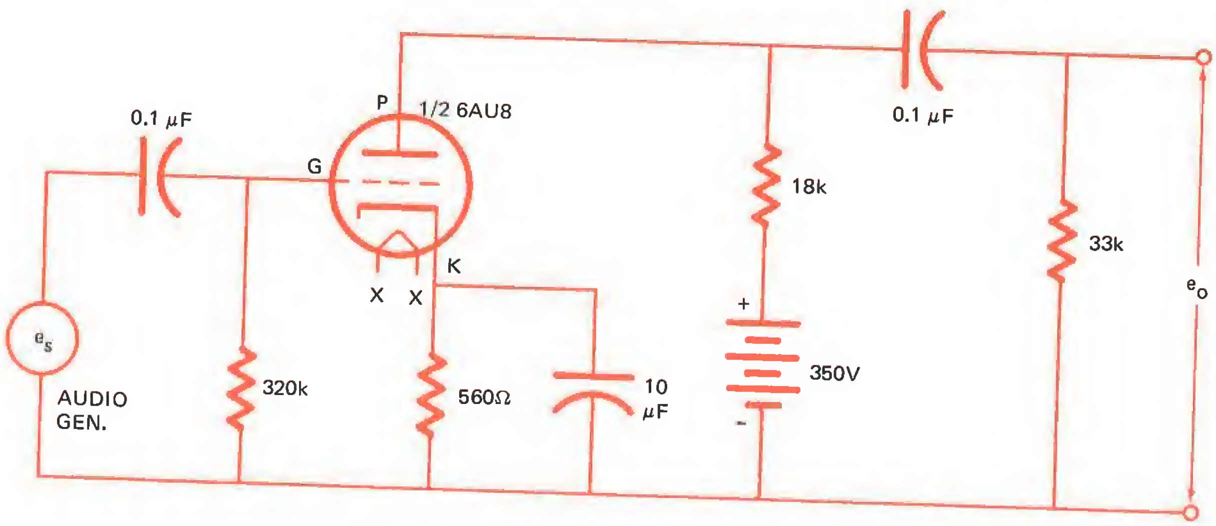


Fig. 12-5 The Triode Experimental Circuit

2. Plot the bias line and locate the Q-point. Record the values of E_{PK}, I_P, and E_G.
3. Compute the value of the AC load resistance R'_L and plot the AC loadline.
4. Assuming an AC input voltage of 2 volts, peak-to-peak, determine the peak-to-peak output voltage.
5. Determine the voltage gain and power sensitivity.
6. Assemble the circuit (do not forget to connect the filament to its rated voltage). Set the audio generator for zero output.
7. Measure and record the values of E_{PK}, I_P, and E_G.
8. Connect the oscilloscope for measuring the audio generator signal and set the generator for a 2-volt peak-to-peak output at 1 kHz. Make a sketch of the input waveform.
9. Move the oscilloscope to the output of the amplifier. Measure and record the peak-to-peak output voltage. Make a sketch of the output waveform.
10. Using the values from steps 8 and 9, compute and record the value of the amplifier's voltage gain.
11. Using measured values (and the value of R) compute and record the power sensitivity of the stage.
12. Disassemble the circuit.
13. Using the pentode output characteristics plot the DC loadline for the circuit shown in figure 12-6.

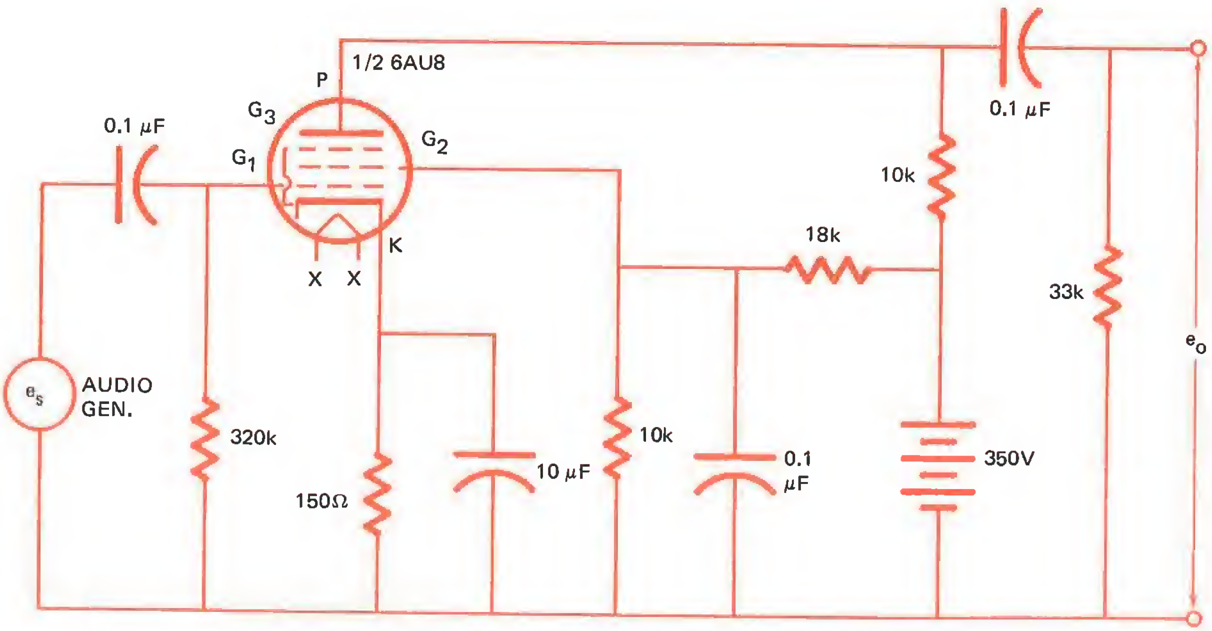


Fig. 12-6 The Pentode Experimental Circuit

14. Repeat steps 2 through 12 using the pentode circuit. Do not forget to include the screen current in determining the Q-point.

Qty.	E_{PK}	I_P	E_G	R'_L	$\frac{e_o}{(P-P)}$	A_v	Power Sens.
Graphical Values							
Measured Values							

Fig. 12-7(a) Triode Amplifier Data

Qty.	E_{PK}	I_P	E_G	R'_L	$\frac{e_o}{(P-P)}$	A_v	Power Sens.
Graphical Values							
Measured Values							

Fig. 12-7(b) Pentode Amplifier Data

ANALYSIS GUIDE. The purpose of this experiment has been to compare values arrived at through graphical analysis to those measured in an actual circuit. In analyzing these data you should evaluate the extent to which this objective was reached. In particular evaluate the effectiveness of loadline analysis in predicting circuit performance.

PROBLEMS

1. Explain in quantitative terms the effect that ignoring the screen current would have had on your results in the experiment.
2. Compute the reactances of the capacitors in the experiment and compare each one to the resistor it is working with. Do you feel that the assumption used in the analysis (that the reactances could be considered zero) was reasonable?

3. What would have been the voltage gain of the triode amplifier in the experiment if the load resistor (R) had been 1 megohm?
4. Repeat problem 3 for the pentode circuit.
5. Which of the two amplifier circuits in the experiment had the higher power gain? Would this always be the case?

experiment 13 FET AMPLIFIER GRAPHICAL ANALYSIS

INTRODUCTION. The field effect transistor is rapidly becoming one of the most important electronic devices. In this experiment we shall examine the graphical technique of analyzing an FET amplifier.

DISCUSSION. The quiescent operating point of the FET amplifier shown in figure 13-1 may be determined by plotting the DC load-line and the bias line, as indicated in figure 13-2. The DC loadline may be constructed by writing the drain circuit loop equation,

$$V_{DD} - I_D R_D - V_{DS} - I_D R_S = 0 \qquad (13.1)$$

This equation may be solved for I_D in terms of V_{DS}

$$\boxed{I_D = \frac{-1}{R_D + R_S} V_{DS} + \frac{V_{DD}}{R_D + R_S}}$$

This line extends from V_{DD} on the drain voltage axis to $I_D = V_{DD}/(R_D + R_S)$ on the drain current axis. This line is shown in figure 13-2 for circuit values of:

$V_{DD} = 20$ volts $\qquad R_D = 2200$ ohms
$R_G = 1$ megohm $\qquad R_S = 200$ ohms
$R = 2200$ ohms $\qquad e_s = 0.3 \sin \omega t$ volts

To plot the bias line we must write the output loop equation

$$V_{DD} - I_D R_D - V_{DS} - I_D R_S = 0$$

or

$$V_{DD} - V_{DS} - I_D (R_D + R_S) = 0$$

However, we recall that the bias voltage (E_G) is related to the drain current by $I_D = -E_G/R_S$.

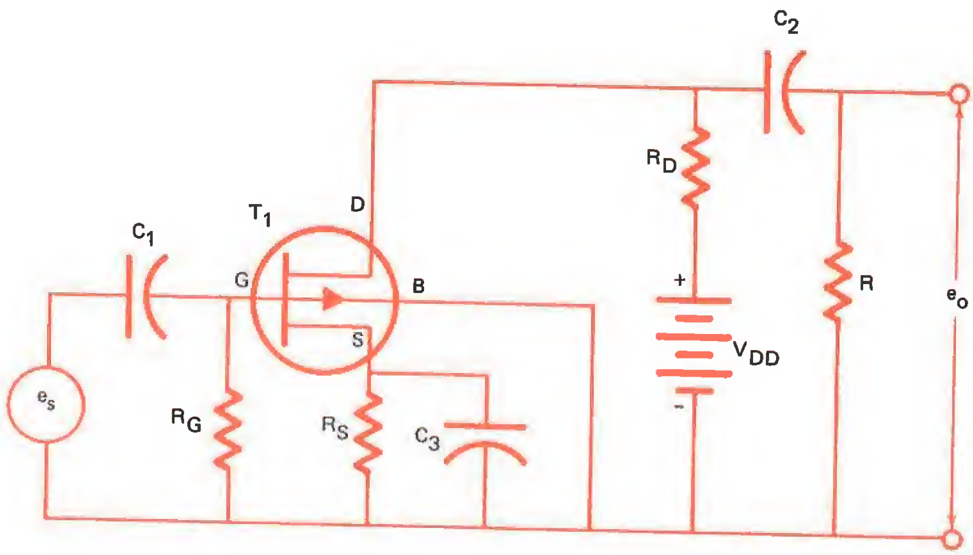


Fig. 13-1 A Typical FET Amplifier Circuit

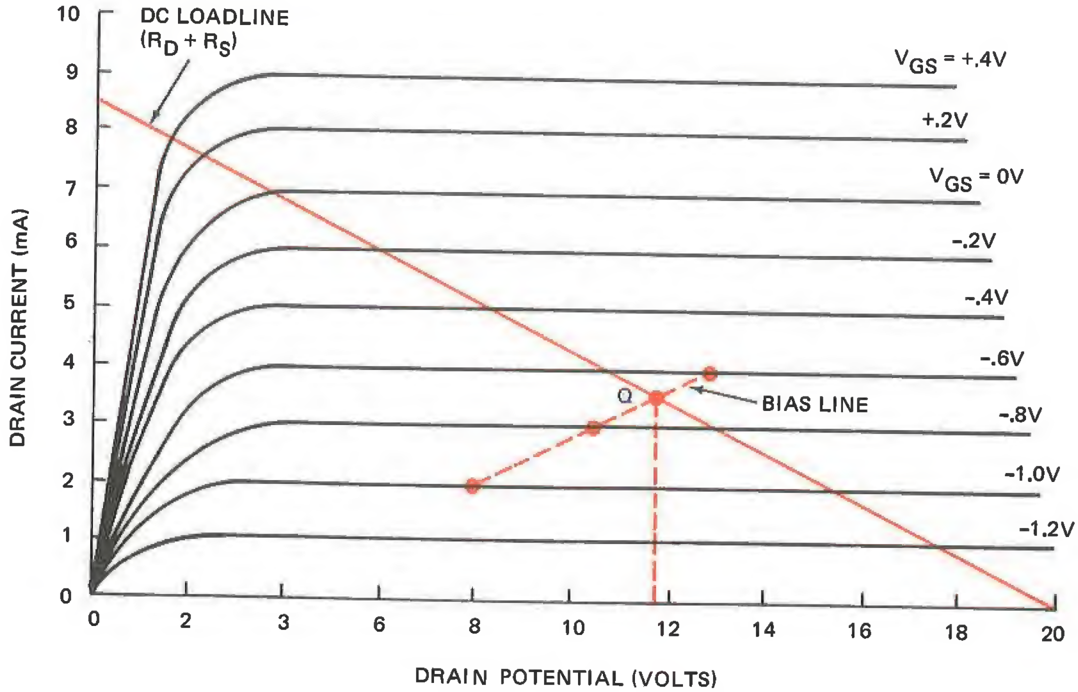


Fig. 13-2 Locating the FET's Q-Point

Substituting this value of I_D into the loop equation gives

$$V_{DD} - V_{DS} + E_G \frac{R_D + R_S}{R_S} = 0$$

which may be solved for V_{DS} rendering

$$\boxed{V_{DS} = V_{DD} + E_G \left(\frac{R_D + R_S}{R_S}\right)} \qquad \textbf{(13.2)}$$

Using the circuit values specified above gives us

$$V_{DS} = 15 + 9.33\, E_G$$

And if we choose values of -0.60, -0.80 and -1.00 volts for E_G, we have

E_G (volts	-0.6	-0.8	-1.0
V_{DS} (volts)	12.8	10.4	8.0

Plotting these points reveals that the Q-Point is located at $V_{DS} \approx 12V$, $I_D \approx 3.5$ mA, and $V_{GS} \approx -0.7V$, as indicated in figure 13-2. These values could, of course, be measured in a functioning circuit.

If we now direct our attention to the AC operation of the circuit, we see that, if the various capacitors are assumed to be short circuits at the input frequency, then the AC equivalent circuit may be drawn as shown in figure 13-3. (The drain supply, V_{DD}, is also assumed to be a short circuit so far as AC is concerned.)

The total effective load (R_L) presented to an AC drain current will be the parallel equivalent of R_D and R.

$$R_L = \frac{R_D R}{R_D + R} \qquad \textbf{(13.3)}$$

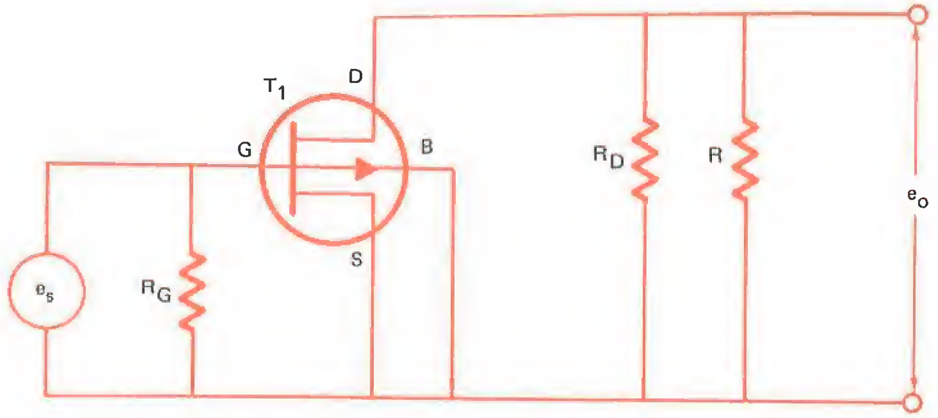


Fig. 13-3 The AC Equivalent Circuit

And the drain circuit loop equation will be

$$V_{DS} = -i_D R_L \quad \text{or} \quad i_D = -\frac{1}{R_L} V_{DS} \qquad (13.4)$$

We may draw this relationship as an AC loadline passing through the Q-point and having a slope of $-1/R_L$. The previous characteristic is shown with this line plotted in figure 13-4.

To make the plot of the AC loadline, we first compute

$$-\frac{1}{R_L} = -\frac{R_D + R}{R_D R} = -\frac{2200 + 2200}{(2200)(2200)}$$

$$= -0.91 \times 10^{-3} \text{ mhos}$$

Then we compute the change in I_D which would accompany a chosen change in V_{DS}.

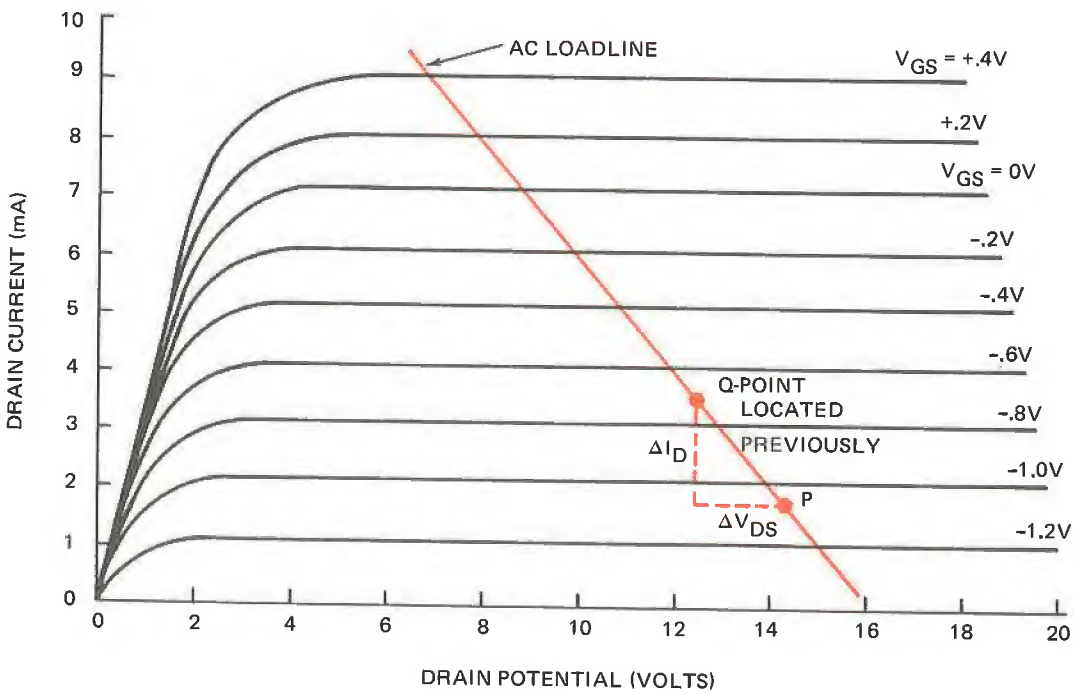


Fig. 13-4 The AC Loadline

If we choose ΔV_{DS} as +2.0 volts, then we have

$$\Delta I_{DS} = -\frac{1}{R_L}\Delta V_{DS} = -0.91 \times 10^{-3} \times 2$$

$$= -1.82 \text{ mA}$$

Then starting at the Q-point, we move down 1.82 mA and over 2 volts to point P. Finally, we draw the AC loadline through P and Q.

With the AC loadline plotted, we may determine several other factors of amplifier performance. For example, the voltage gain of the stage is defined as

$$\boxed{A_v = \frac{e_o}{e_s}} \qquad (13.5)$$

If we apply the input AC signal ($e_s = 0.3 \sin \omega t$) to the Q-point, the gate-to-source voltage will swing from -0.4 volts to -1.0 volts. The resulting swing in drain-to-source voltage would be from approximately 10.1 volts to 13.9 volts which is a peak-to-peak voltage of 3.8 volts ($E_{p\text{-}p}$ = 13.9 - 10.1 volts). We may therefore describe the output voltage as

$$e_o = V_{DS} = -1.9 \sin \omega t$$

The minus sign indicates the apparent phase reversal (as V_{GS} increases, V_{DS} decreases).

The voltage gain is therefore

$$A_v = \frac{e_o}{e_s} = \frac{-1.9 \sin \omega t}{0.3 \sin \omega t} \approx 6.33$$

The input current is a function of R_G

$$i_s = \frac{e_s}{R_G}$$

if the gate current of the FET is zero. As a result, the current gain ($A_i = \frac{i_L}{i_s}$) may be varied simply by changing the value of R_G. Consequently, the current gain of the stage is usually of no interest.

Similarly, the power gain ($A_p = |A_i|\,|A_v|$) is of only small interest in most cases. However, it is customary to discuss amplifiers of this type in terms of their *power sensitivity.* Power sensitivity is defined as the power output per square rms volts of input. That is

$$\text{Power sens} = \frac{P_o}{E_s^2} \qquad (13.6)$$

Since we may compute the output power using the resistance (R) and the rms output voltage

$$P_o = \frac{E_o^2}{R}$$

equation 13.6 becomes

$$\boxed{\text{Power sens} = \left(\frac{E_o^2}{E_s^2}\right)\frac{1}{R} = \frac{|A_v|^2}{R}} \qquad (13.7)$$

which is a convenient form for use with graphical data.

MATERIALS

1 MOSFET type 40468 or equivalent
1 Set of output characteristics for the FET
1 Transistor socket
1 100Ω resistor 1/2W
1 1kΩ resistor 1/2W
1 1-megohm resistor 1/2W
3 10-μF, 50W VDC capacitors
1 Resistance substitution box (0 - 10 megohm 1/2W)
1 VOM or FEM
1 Audio generator
1 Oscilloscope
1 Variable DC power supply (0 - 40V)
1 Sheet of linear graph paper

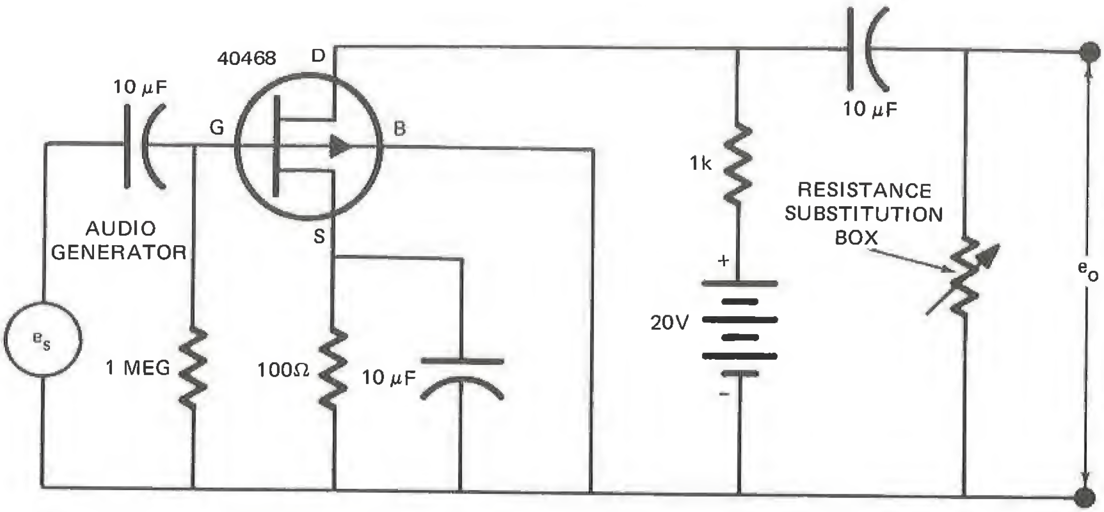


Fig. 13-5 The Experimental Amplifier Circuit

PROCEDURE

1. On the FET output characteristic, plot the DC loadline for the circuit shown in figure 13-5.
2. Also plot the bias line and locate the Q-point. Record the values of V_{DS}, I_D, and V_{GS}.
3. Set the resistance substitution box for 2.2k and plot the AC loadline on the output characteristic. Record the value of R_L in the data table.
4. Graphically determine and record the values of the voltage gain and the power sensitivity. Assume e_s is one volt peak-to-peak.
5. Repeat steps 3 and 4 for resistance substitution box values of 4.7k, 10k, 22k and 47k ohms.
6. Assemble the circuit exercising appropriate precautions against electrostatic damage to the FET gate insulation. Set the input e_s to zero and the resistance substitution box to 47k.
7. Measure and record the values of V_{DS}, I_D, and V_{GS} using a VOM.
8. Connect the oscilloscope for measuring the value of e_s. Set the audio generator for an output of one volt peak-to-peak at a frequency of 1 kHz. Make an accurate sketch of the input waveform.
9. Compute and record the value of the reactance (X_c) of a 10-μF capacitor at 1 kHz.
10. Move the oscilloscope to the output and record the peak-to-peak value of e_o. Make an accurate sketch.
11. Using the values of e_s and e_o, compute the actual voltage gain of the amplifier.
12. Compute the power sensitivity of the amplifier using the resistance substitution box setting and the value of A_v determined in step 11.

13. Repeat steps 7, 8, 10, 11, and 12 for resistance substitution box settings of 22k, 10k, 4.7k, and 2.2k.

14. Plot a curve of the amplifier voltage versus the load resistance (resistance on the horizontal axis).

V_{DS} (Volts)	I_D (mA)		V_{GS} (Volts)		X_C @ 1 kHz (ohms)
Resistance Box Value	2.2k	4.7k	10k	22k	47k
R_L =					
A_v =					
Power sens =					

(A) COMPUTED DATA

Resistance Box Setting	2.2k	4.7k	10k	22k	47k
V_{DS} (volts)					
I_D (mA)					
V_{GS} (volts)					
e_s (volts p-p)					
e_o (volts p-p)					
A_v					
Power sens.					

(B) MEASURED DATA

Fig. 13-6 The Data Table

ANALYSIS GUIDE. In analyzing these data, you should be primarily concerned with the validity of the analysis techniques used, and in particular, consider the following specific points:

1. Did the Q-point shift as the load on the amplifier changed? Why?
2. Did the computed and measured values of voltage gain and power sensitivity agree?
3. Did the input or output waveform change shape as the load changed? Why?

PROBLEMS

1. Would the Q-point of an FET shift if the total drain circuit resistance ($R_D + R_S$) was held constant while the ratio of R_D to R_S was varied? Illustrate your answer with a numerical example.

2. A certain amplifier has a power sensitivity of 0.01 watts per volt squared when operating a 10k ohm load. What is the voltage gain?

3. If the load on a stage is increased (R is made smaller), will the voltage gain increase or decrease? Will the current gain increase or decrease? Will the power gain increase or decrease? Illustrate your answers with an example showing the AC loadline for each case.

experiment 14 SMALL-SIGNAL PARAMETERS

INTRODUCTION. In many practical cases, an amplifier must handle very small signal levels. In this experiment we shall explore ways in which amplifier circuit analysis may be approached when the signal levels are too small to plot on the output characteristic curves.

DISCUSSION. In analyzing the small signal performance of an amplifier, we establish the quiescent operating point using the bias and loadline. When the very small AC signal is applied, we assume that the variation around the Q-point will be small and linear; then *we consider only the AC operation* of the amplifier.

Consider the simplified amplifier stage shown in figure 14-1. The input voltage (V_{BE}) and output current (i_C) must both be linear functions of the input current (i_B) and the output voltage (V_{CE}).

In many cases the relationships used to represent the transistor are

$$V_{BE} = h_{ie}i_B + h_{re}V_{CE} \tag{14.1}$$

and

$$i_C = h_{fe}i_B + h_{oe}V_{CE} \tag{14.2}$$

where:

$h_{ie} = \dfrac{\partial V_{BE}}{\partial i_B}$ and is the dynamic input resistance when V_{CE} is constant.

$h_{re} = \dfrac{\partial V_{BE}}{\partial V_{CE}}$ and is the reverse voltage amplification when i_B is constant.

$h_{fe} = \dfrac{\partial i_C}{\partial i_B}$ and is the forward current amplification when V_{CE} is constant.

$h_{oe} = \dfrac{\partial i_C}{\partial V_{CE}}$ and is the dynamic output admittance when i_B is constant.

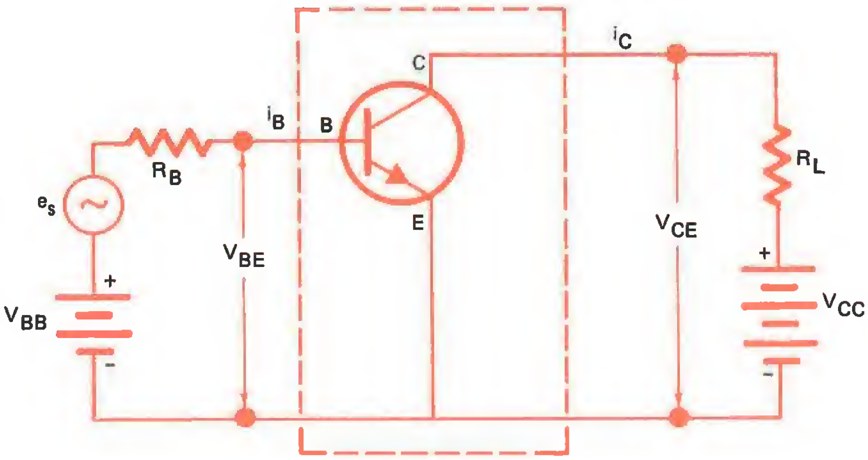


Fig. 14-1 A Simplified Amplifier Circuit

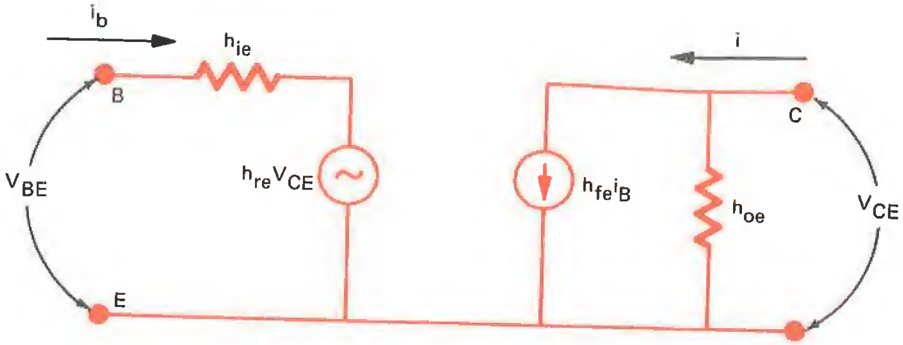


Fig. 14-2 Transistor Hybrid Equivalent Circuit

These quantities are referred to as the *h-parameters* for the common emitter configuration.

Based on these equations, we can draw the *hybrid equivalent circuit* of the transistor as shown in figure 14-2. Notice that equation 14.1 describes only the input half of the equivalent circuit, while equation 14.2 applies only to the output side of the equivalent circuit.

Take particular notice of the fact that this is the equivalent circuit of the transistor alone and does not include the components used with the transistor in an amplifier circuit.

Most modern small-signal transistors are sufficiently linear that we can usually use a much simpler equivalent circuit than the one shown in figure 14-2. One such simplified equivalent circuit is the *hybrid-π* arrangement shown in figure 14-3.

In this equivalent circuit the value of the transconductance g_m will usually be quite close to

$$\boxed{g_m = 39\, I_C \text{ mhos}}$$

and the input resistance is

$$\boxed{r_\pi = \frac{h_{fe}}{g_m}}$$

The main advantage of this small-signal equivalent is that it involves only the two param-

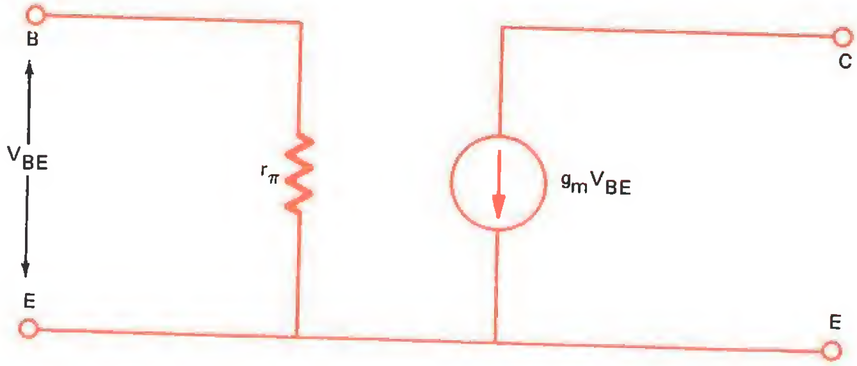


Fig. 14-3 The Hybrid-π Equivalent Circuit

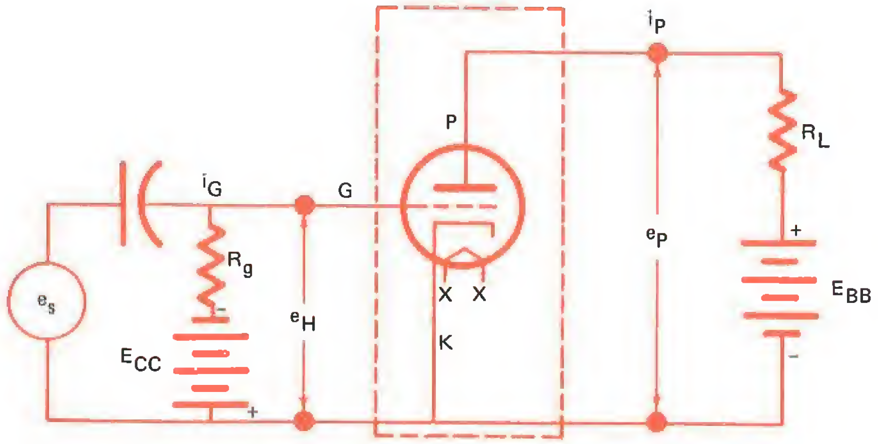


Fig. 14-4 A Simplified Vacuum Tube Amplifier Circuit

eters r_π and g_m, instead of the four h-parameters. Also it includes parameter changes due to Q-point shift by using I_C in the g_m definition.

Vacuum tubes may be analyzed in very much the same way. For example, consider the simplified vacuum tube circuit shown in figure 14-4. As before, we observe that the output current (i_P) must be a function of the output voltage (e_P) and some input variable. Since the input current (i_G) will be zero for practical purposes, then we use the input voltage (e_G) as the input variable. The equation frequently used is

$$\boxed{(i_P) = g_m e_G + \frac{1}{r_P} e_P} \qquad \textbf{(14.3)}$$

where:

$g_m = \dfrac{\partial i_P}{\partial e_G}$ and is the dynamic transconductance when e_P is constant.

$r_P = \dfrac{\partial e_P}{\partial i_P}$ and is the dynamic output (plate) resistance when e_G is constant.

From this equation we can draw the equivalent circuit for a vacuum tube as shown in figure 14-5. This is the equivalent circuit of the tube alone and does not include other amplifier circuit components.

It is worth noting at this point that there

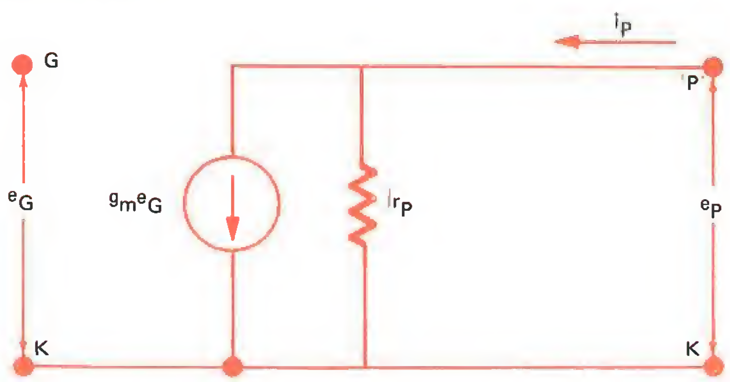


Fig. 14-5 The $g_m e_G$ Equivalent Circuit for Vacuum Tubes

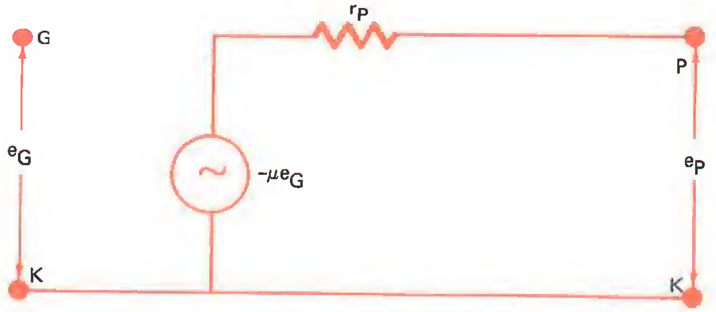


Fig. 14-6 The e_G Equivalent Circuit for Vacuum Tubes

is a third commonly used vacuum tube small-signal parameter called mu (μ) which is the product of g_m and r_P.

$$\boxed{\mu = g_m r_P} \qquad (14.4)$$

If we multiply equation 14.3 by r_P, we have

$$i_P r_P = g_m r_P e_G + e_P$$

or

$$e_P = i_P r_P - g_m r_P e_G$$

And since $\mu = g_m r_P$, we have

$$e_P = i_P r_P - \mu e_G \qquad (14.5)$$

Using this equation, we may draw a second vacuum tube equivalent circuit, as shown in figure 14-6. Returning to the definition of $\mu (\mu = g_m r_P)$ and recalling that $g_m = \partial i_P/\partial e_G$ while $r_P = \partial e_P/\partial i_P$, we have

$$\mu = g_m r_P = \frac{\partial i_P}{\partial e_P} \cdot \frac{\partial e_P}{\partial i_P} = \frac{\partial e_P}{\partial e_G}$$

Consequently, μ may be interpreted as the forward voltage *amplification factor* when i_P is constant.

Both of the vacuum tube equivalent circuits are useful. The first one (figure 14-5) is usually used with pentode tubes while the second (figure 14-6) is most useful with triodes.

Field effect transistors are also frequently used as small-signal amplifiers. Figure 14-7 shows a simplified FET amplifier circuit.

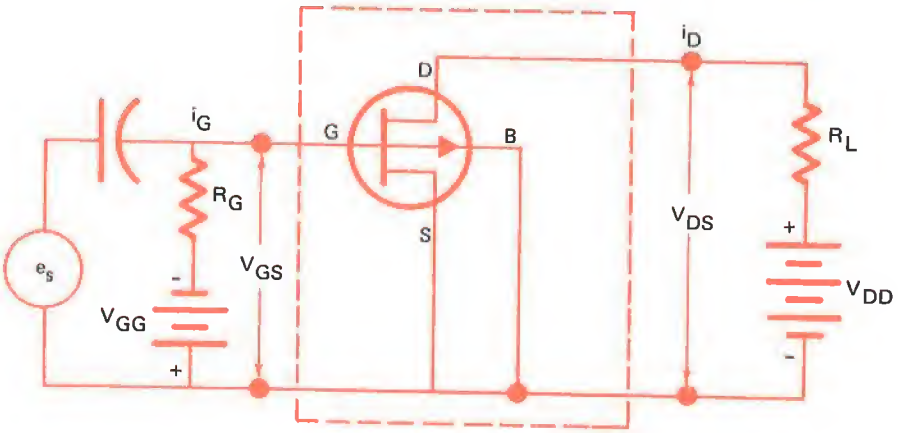


Fig. 14-7 A Simplified FET Amplifier Circuit

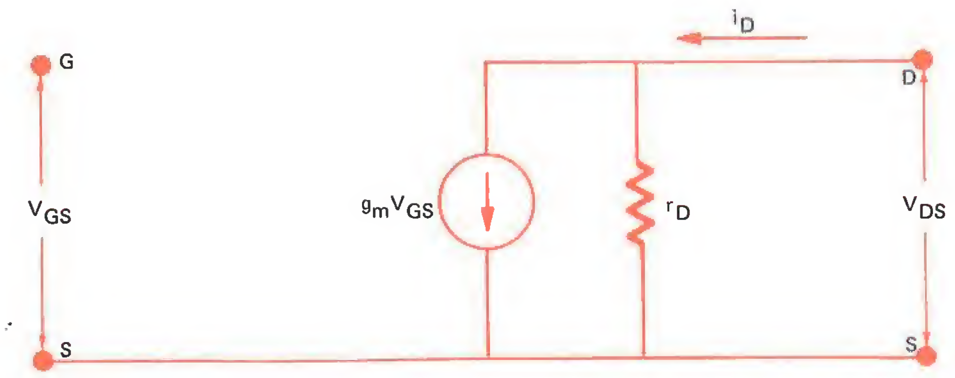


Fig. 14-8 An FET Equivalent Circuit

As before, we can observe that the drain current will be a function of the drain voltage and the gate voltage ($i_G \cong 0$). The equation frequently used to describe the FET is

$$\boxed{i_D = g_mV_{GS} + \frac{1}{r_D}V_{DS}} \qquad \textbf{(14.6)}$$

where g_m and r_D are defined the same as g_m and r_P for a vacuum tube. We can draw the equivalent circuit shown in figure 14-8.

In the case of an FET, we can also define the forward voltage amplification factor as $\mu = g_mr_D$. However, the μ factor is rarely used in analyzing FET circuits.

The small-signal parameters for a particular device (transistor, tube, or FET) may be determined in several ways:

(a) Manufacturers often supply data sheets showing typical parameter values.

(b) They may be approximated using the input and output characteristics of the device.

(c) They may be measured.

The first alternative will not be examined further in this discussion; however, you may wish to look at some typical data sheets yourself.

Let's look at the second method more closely. The values of h_{ie} and h_{re} for a transistor may be approximated from the input characteristic. h_{ie} is defined as

$$h_{ie} = \frac{\partial V_{BE}}{\partial I_B}$$

and may be approximated by

$$h_{ie} \simeq \frac{\Delta V_{BE}}{\Delta I_B}$$

when V_{CE} is constant. This relationship can be evaluated graphically as indicated in figure 14-9a.

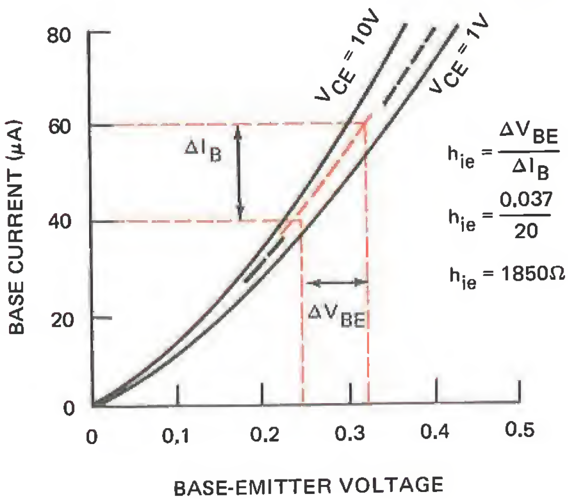


Fig. 14-9a Approximating h_{ie}

On the other hand,

$$h_{re} = \frac{\partial V_{BE}}{\partial V_{CE}}$$

can be approximated by

$$h_{re} \simeq \frac{\Delta V_{BE}}{\Delta V_{CE}}$$

when I_B is constant. Graphic evaluation of this approximation is shown in figure 14-9b.

On the other hand, h_{fe} being defined as

$$h_{fe} = \frac{\partial i_C}{\partial i_B}$$

may be approximated by

$$h_{fe} \simeq \frac{\Delta I_C}{\Delta I_B} \quad \text{when } V_{CE} \text{ is constant}$$

while

$$h_{oe} = \frac{\partial i_C}{\partial V_{CE}}$$

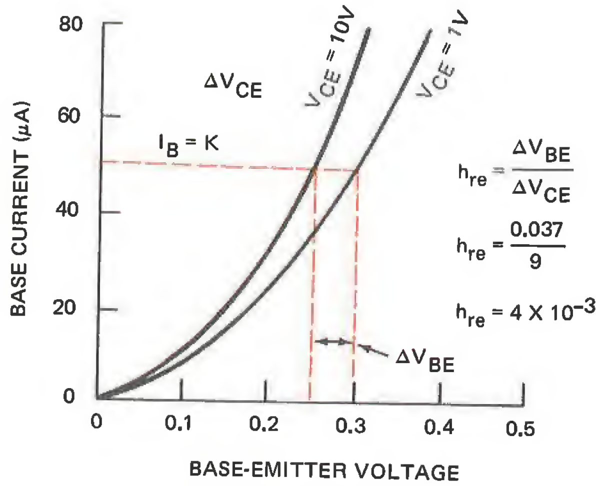
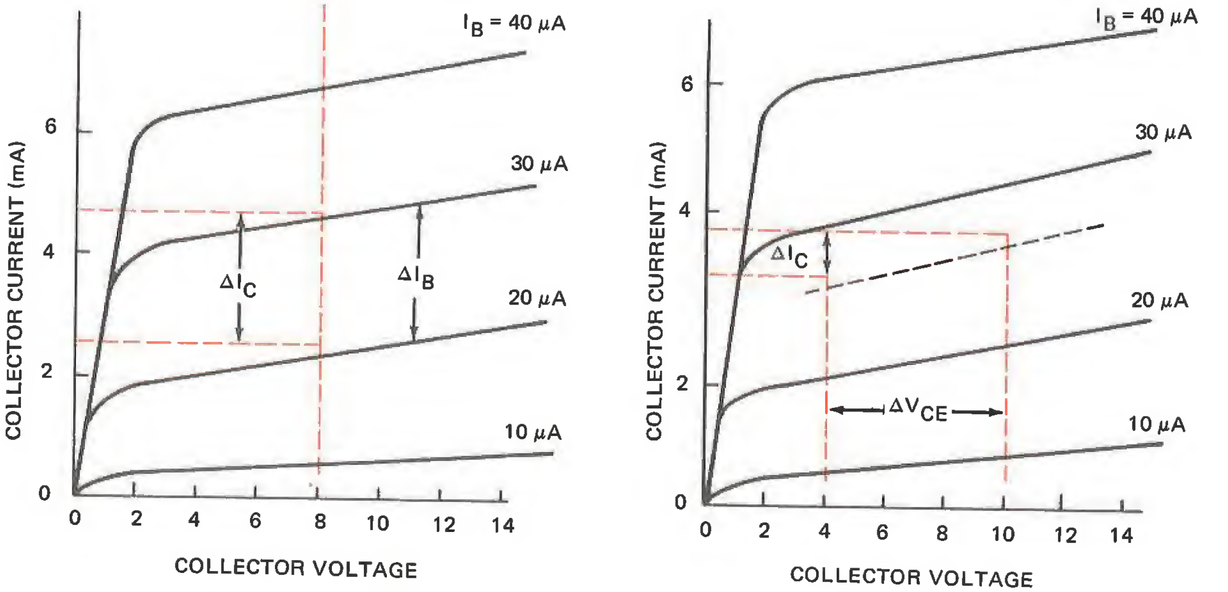


Fig. 14-9b Determining h_{re} Graphically

and can be approximated using

$$h_{oe} \simeq \frac{\Delta I_C}{\Delta V_{CE}} \quad \text{when } I_B \text{ is constant}$$

These two parameters may be found graphically using the transistor output characteristics as indicated in figure 14-10.



$$h_{fe} = \frac{\Delta I_C}{\Delta I_B} = \frac{2\text{ mA}}{10\ \mu\text{A}} = 200$$

$$h_{oe} = \frac{\Delta I_C}{\Delta V_{CE}} = \frac{0.5\text{ mA}}{6\text{V}} = 83 \times 10^{-6}\text{ mhos}$$

(A) DETERMINING h_{fe} *(B) DETERMINING h-PARAMETERS GRAPHICALLY*

Fig. 14-10 Determining h-Parameters Graphically

For Tubes	For FETs
$r_P = \frac{\partial e_P}{\partial i_P} \approx \left.\frac{\Delta E_P}{\Delta I_P}\right\rvert_{E_C = K}$	$r_D = \frac{\partial e_D}{\partial i_D} \approx \left.\frac{\Delta E_D}{\Delta I_D}\right\rvert_{I_G = K}$
$g_m = \frac{\partial i_P}{\partial e_G} \approx \left.\frac{\Delta I_P}{\Delta E_G}\right\rvert_{E_P = K}$	$g_m = \frac{\partial i_D}{\partial e_G} \approx \left.\frac{\Delta I_D}{\Delta E_G}\right\rvert_{E_D = K}$
$\mu = \frac{\partial e_P}{\partial e_G} \approx \left.\frac{\Delta E_P}{\Delta E_G}\right\rvert_{I_P = K}$	

Small-signal parameter values for tubes and Field Effect transistors are determined in the same way as those illustrated above. Of course, since FETs and tubes do not require significant amounts of input current, all of their small-signal parameters may be found using only the output characteristics. The approximations used are shown in the table above.

In measuring the small-signal parameters of a device, we hold one variable constant, vary a second, while measuring a third as well as the first two. For example, if we wish to measure the g_m of an FET, the circuit shown in figure 14-11 could be used. The quiescent operating conditions are established as usual. The audio generator provides a varying gate voltage (∂V_{GS}) which is measured by the AC voltmeter. The varying drain current (∂i_D) is measured with the AC ammeter. At the same time, the value of the drain-to-source voltage (V_{DS}) is held constant at the Q-point value by the bypass capacitor C_1 and the source resistor bypass capacitor C_S. We may, therefore, calculate the value of g_m (in mhos) by dividing the ammeter reading (in amps) by the voltmeter reading (in volts):

$$g_m = \frac{\partial i_D}{\partial V_{GS}} \quad \text{when } V_{DS} \text{ is constant}$$

We shall use methods similar to the one above to measure some of the small-signal parameters.

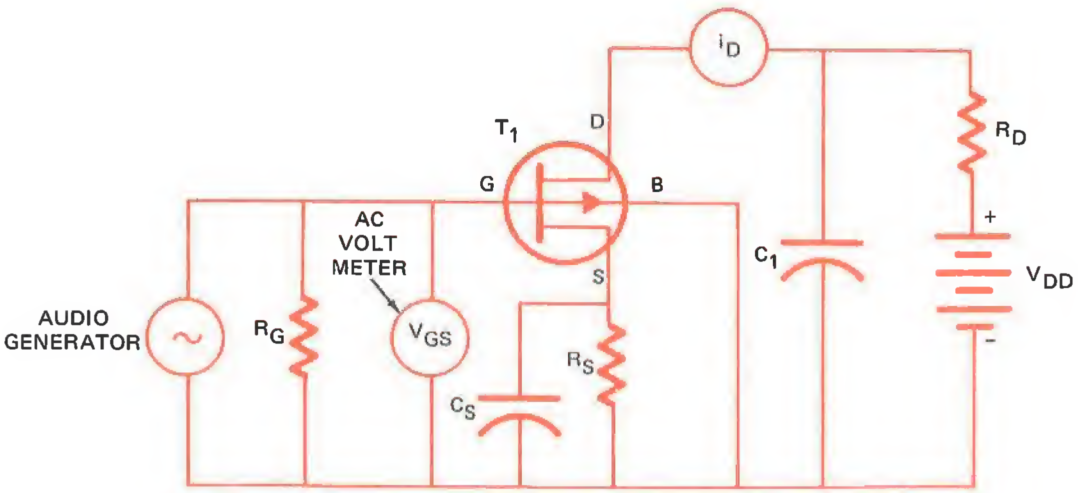


Fig. 14-11 A Circuit for Measuring g_m

MATERIALS

1 MOSFET type 40468 or equivalent
1 Transistor type 2N1304 or equivalent
1 Complete set of characteristics for above devices
1 Transistor socket
1 Variable DC supply (0 - 40V)
2 VOMs or FEMs
2 330k ohm resistors 2W
2 220-ohm resistors
1 1k ohm resistor
1 1.8k ohm resistor
1 2.2k ohm resistor
3 10 μF 50W VDC capacitors
1 Set of vacuum tube output characteristics
1 Audio generator

PROCEDURE

1. Using the transistor output characteristics, graphically determine the value of h_{fe} near V_{CE} = 2 volts and I_B = 25 μA.
2. Assemble the circuit shown in figure 14-12.

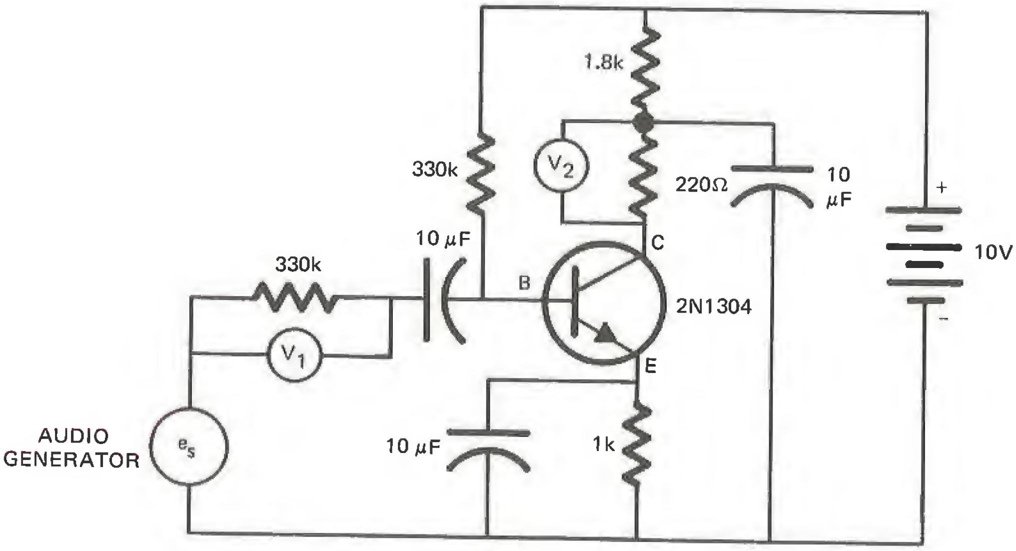


Fig. 14-12 Circuit for Measuring h_{fe}

3. Connect a meter across the 330k resistor and set the audio generator for a reading of 2.5 volts rms at 1 kHz.
4. Compute and record the AC base current ∂i_B.
5. Connect another meter across the 220-ohm collector resistor and record the AC voltage at this point (e_{AC}).
6. Compute and record the AC collector current ∂i_C.
7. Compute h_{fe}. Record this value as a measured quantity.

8. Using the FET output characteristic, graphically determine the value of r_D in the region near V_{DS} = 7 volts and V_{GS} = −1.0 volts.

9. Assemble the circuit shown in figure 14-13. Observe the necessary precautions to prevent electrostatic damage to the FET.

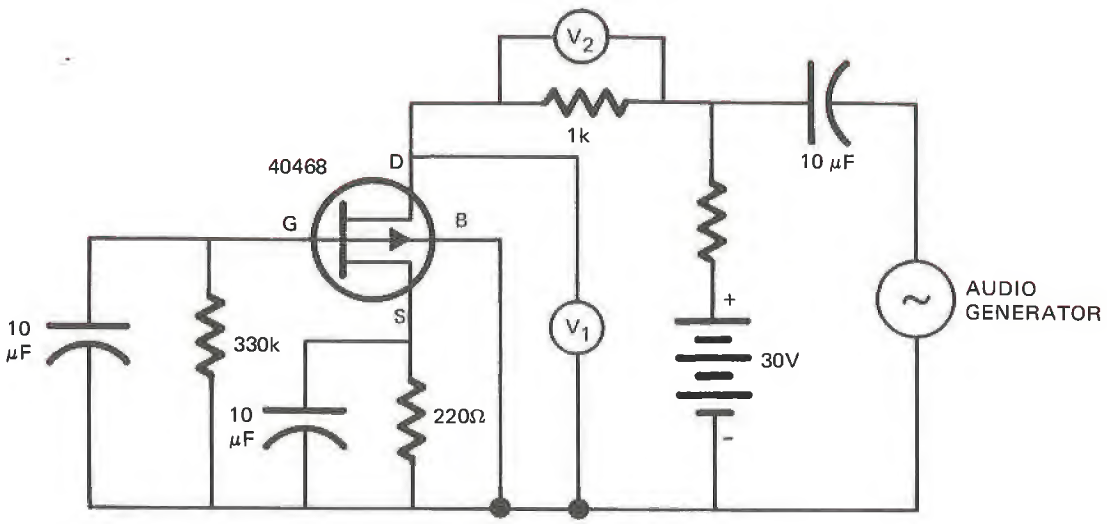


Fig. 14-13 Circuit for Measuring r_D

10. Adjust the audio generator output frequency to 1 kHz and the output level for readable values on the two meters.

11. Record the AC voltage from drain-to-source as ∂V_{DS}.

12. With the VOM reading, compute and record the AC drain current ∂i_D.

13. Compute and record the value of r_D.

14. With the FET output characteristics, graphically determine the value of g_m near V_{DS} = 10 volts and I_D = 6 mA.

15. Assemble the circuit shown in figure 14-14.

16. Adjust the audio generator to 1 kHz and a VTVM reading just large enough to read accurately. Record this value as ∂V_{GS}.

17. Measure and record the voltage across the 220-ohm drain resistor. (e_{AC})

18. Compute and record the AC drain current, ∂i_D.

19. Compute and record g_m.

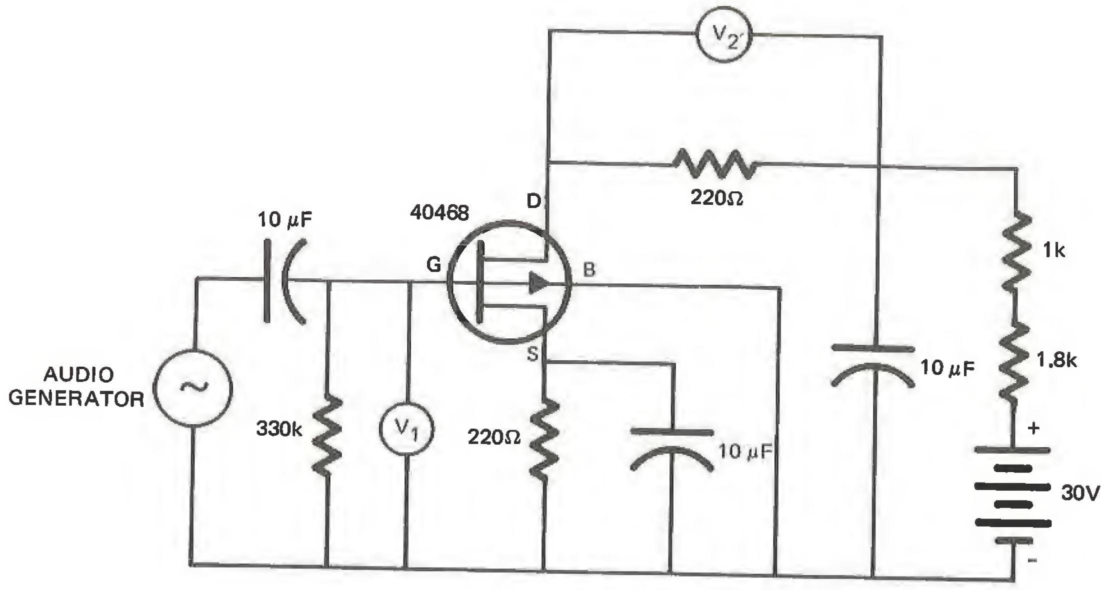


Fig. 14-14 Circuit for Measuring g_m

	h_{fe}	r_D	g_m
Values from Characteristic curves			

Transistor Data	
∂i_B	
e_{AC}	
∂i_C	
h_{fe}	

FET Data	
∂V_{DS}	
∂i_D	
r_D	
∂V_{GS}	
e_{AC}	
g_m	

Fig. 14-15 The Data Table

ANALYSIS GUIDE. In analyzing these data, you should discuss each circuit used and the extent to which your graphically determined values agreed with the measured values.

PROBLEMS

1. Using the output characteristics of the transistor, graphically determine the values of h_{ie}, h_{re}, and h_{oe}.
2. With the vacuum tube characteristics supplied with the experiment, determine the values of g_m, r_P, and μ near E_{PK} = 250 volts, E_G = -2 volts.
3. Draw a circuit diagram for measuring the μ of a triode vacuum tube.
4. Explain how you would determine g_m and r_π for a transistor.

experiment 15 TRANSISTOR AMPLIFIER SMALL-SIGNAL ANALYSIS

INTRODUCTION. Transistors are frequently used as small-signal amplifiers. In this experiment we shall examine the performance of such an amplifier using the small-signal parameters.

DISCUSSION. The common emitter amplifier shown in figure 15-1 is one of the most widely used transistor amplifier circuits. The quiescent operating conditions may be determined using the customary graphical techniques of loadline analysis.

If we are interested in only the AC operation of the circuit, we can simplify it, as shown in figure 15-2. The component values may be found by observing that, from the signal source, R_1 and R_2 appear to be in parallel as do R_C and R. We may, therefore, compute R_B and R_L using

$$R_B = \frac{R_1 R_2}{R_1 + R_2}$$

and

$$R_L = \frac{R_C R}{R_C + R}$$

If we replace the transistor with its hybrid-π equivalent we will have the circuit shown in figure 15-3. To get figure 15-3b we simplify the input circuit using

$$R_S = \frac{R_G R_B}{R_G + R_B} \quad \text{and} \quad e_s = \frac{e_G R_B}{R_G + R_B}.$$

Using this circuit we can write input and output loop equations

$$V_{BE} = i_B r_\pi$$

and

$$i_C = g_m V_{BE}$$

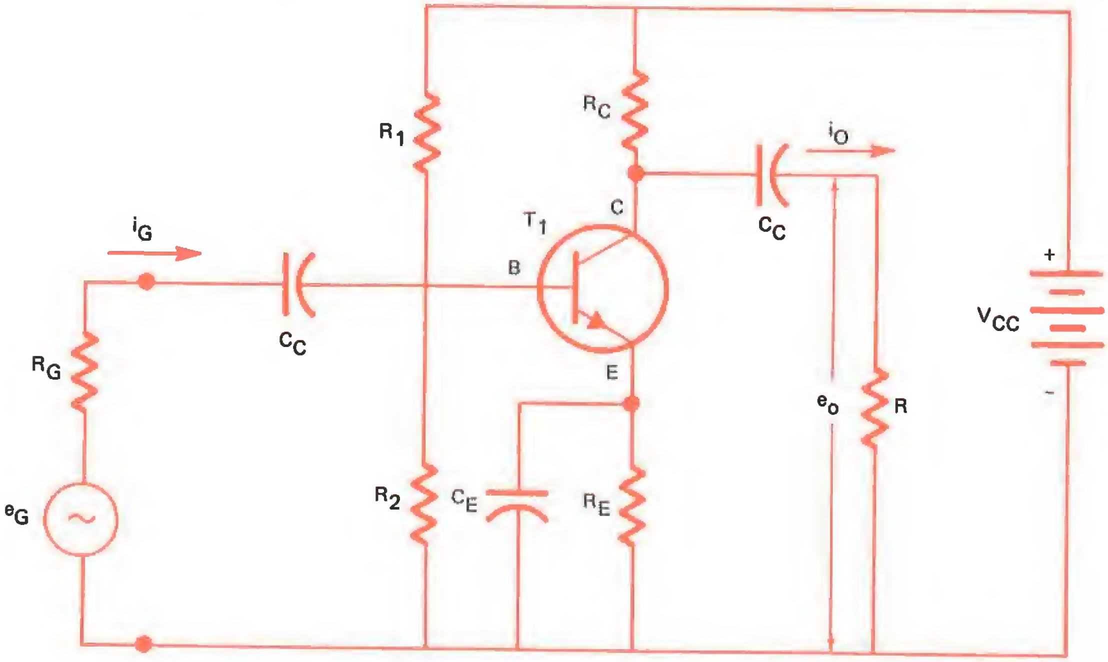


Fig. 15-1 A Typical Transistor Amplifier Circuit

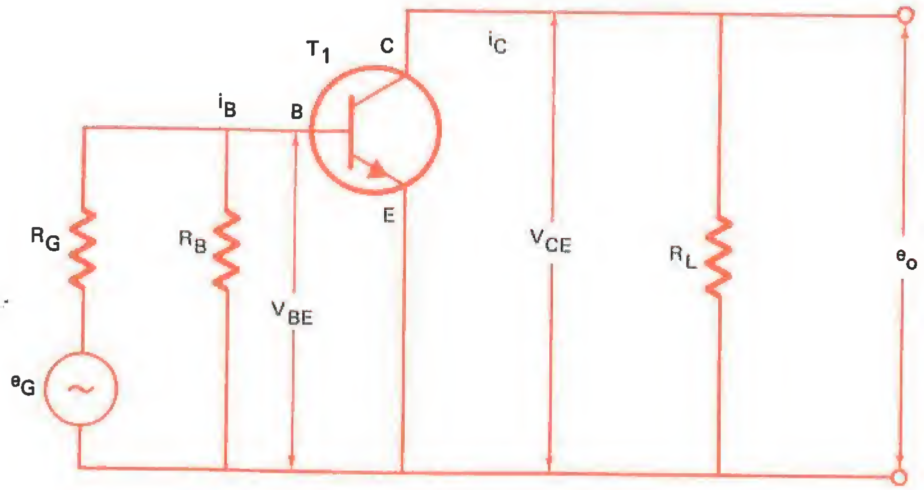
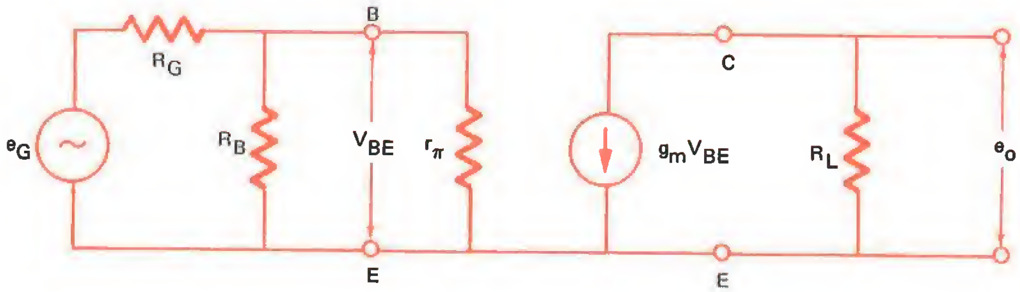
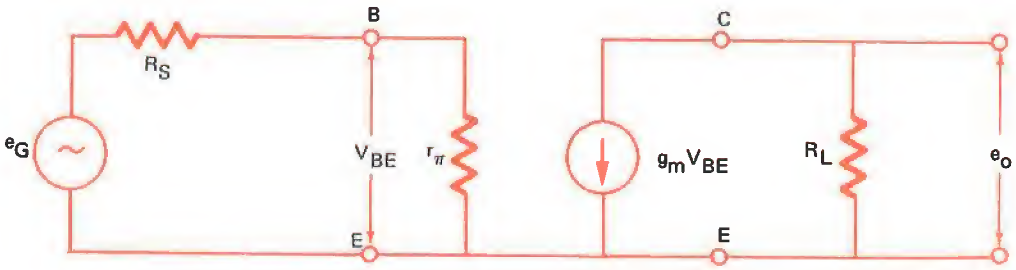


Fig. 15-2 The Simplified AC Equivalent Circuit



(A) CIRCUIT WITH TRANSISTOR EQUIVALENT



(B) CIRCUIT WITH INPUT SIMPLIFIED

Fig. 15-3 The Hybrid-π Equivalent

We can use these two equations to find the five basic amplifier parameters. These parameters are:

1. The current gain ($A_i = i_C/i_B$)
2. The voltage gain ($A_v = V_{CE}/V_{BE}$)
3. The power gain ($A_P = V_{CE}i_C/V_{BE}i_B = |A_i|\,|A_v|$)
4. The input resistance ($R_i = V_{BE}/i_B$)
5. The output resistance ($R_o = V_{CE}/i_C$)

Each of these quantities will be discussed indi-

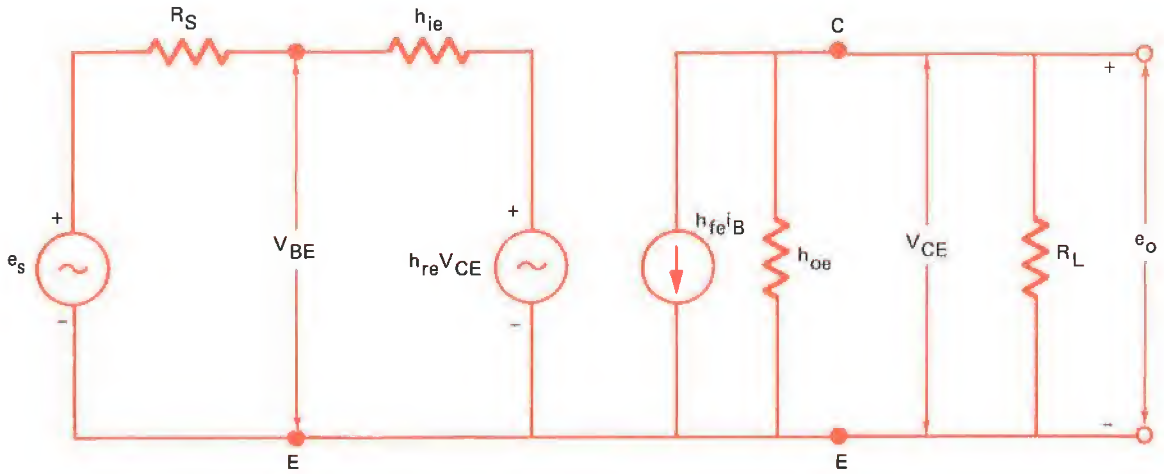


Fig. 15-4 The Hybrid Amplifier Equivalent Circuit

vidually after we have examined another equivalent circuit.

If we replace the transistor with its hybrid equivalent, we will have the hybrid equivalent of the entire stage. This has been done in figure 15-4. The input circuit has also been further simplified by using its Thévenin's equivalent:

$$R_S = \frac{R_G R_B}{R_G + R_B} \quad \text{and} \quad e_s = \frac{e_G R_B}{R_G + R_B}$$

For the input circuit of the transistor we may write the equation

$$V_{BE} = h_{ie} i_B + h_{re} V_{CE} \tag{15.1}$$

And for the output circuit we write

$$i_C = h_{fe} i_B + h_{oe} V_{CE} \tag{15.2}$$

We can use these two equations to find the five basic amplifier parameters listed previously. Each of these quantities are discussed in the following paragraphs.

Current Gain. As suggested above, the current gain of an amplifier is the ratio of the output current to the input current

$$\boxed{A_i = \frac{i_C}{i_B}}$$

From equation 15.2 we have

$$i_C = h_{fe} i_B + h_{oe} V_{CE}$$

And from the hybrid equivalent circuit (figure 15-4), we see that

$$V_{CE} = -i_C R_L$$

Combining these two relationships we have

$$i_C = h_{fe} i_B - h_{oe} i_C R_L$$

Collecting the i_C terms renders

$$i_C + i_C h_{oe} R_L = h_{fe} i_B$$

or

$$i_C (1 + h_{oe} R_L) = h_{fe} i_B$$

Therefore,

$$A_i = \frac{i_C}{i_B} = \frac{h_{fe}}{1 + h_{oe} R_L} \tag{15.3}$$

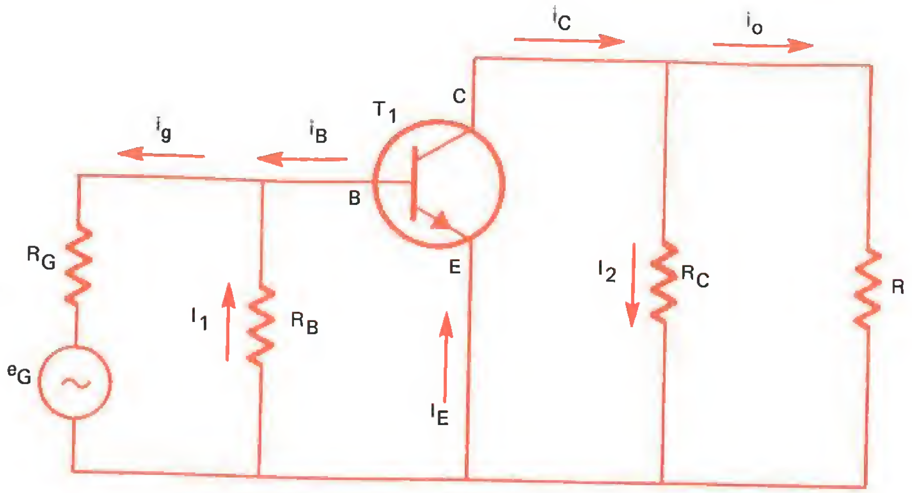


Fig. 15-5 Signal Current in an Amplifier Stage

This equation is commonly used to calculate the current gain of a common emitter transistor amplifier.

It should be noted at this point that, since $h_{oe}R_L$ is often much much less than unity, then

$$\boxed{A_i \approx h_{fe}} \tag{15.4}$$

is frequently a valid approximation for the current gain.

Equations 15.3 and 15.4 apply only to the *transistor,* not to the circuit as a whole. Returning to the original circuit, we see that it could be redrawn as shown in figure 15-5 if the AC action alone is considered.

The base signal current is related to the generator current by

$$i_B = i_g \frac{R_B}{R_B + R_i}$$

while the output current is related to the collector current by

$$i_o = i_C \frac{R_C}{R_C + R}$$

or

$$i_C = i_o \frac{R_C + R}{R_C}$$

The ratio of i_C to i_B is the current gain A_i; therefore,

$$A_i = \frac{i_C}{i_B} = \frac{i_o}{i_g} \frac{(R_C + R)(R_B + R_i)}{R_B R_C}$$

which may be rewritten as

$$\frac{i_o}{i_g} = \frac{R_B R_C}{(R_B + R_i)(R_C + R)} A_i$$

The ratio i_o/i_g can be interpreted as the whole circuit gain (K_i) and we have

$$K_i = \frac{R_B R_C A_i}{(R_B + R_i)(R_C + R)} \tag{15.5}$$

for the entire amplifier circuit.

Voltage Gain. Solving for the voltage gain of a transistor stage is somewhat more involved

than solving for the current gain. As indicated previously, the voltage gain is

$$\boxed{A_v = \frac{V_{CE}}{V_{BE}}}$$

To determine this ratio we must solve equations 15.1 and 15.2 simultaneously. Perhaps the best method is by the use of determinants. The equations to be used are

$$V_{BE} = h_{ie}i_B + h_{re}V_{CE} \qquad (15.1)$$

and

$$i_C = h_{fe}i_B + h_{oe}V_{CE} \qquad (15.2)$$

These equations may be solved for V_{CE} resulting in

$$V_{CE} = \frac{h_{ie}i_C - h_{fe}V_{BE}}{h_{ie}h_{oe} - h_{fe}h_{re}}$$

The denominator of this expression is usually called *delta-h*(Δ_h).

$$\Delta_h = h_{ie}h_{oe} - h_{fe}h_{re} \qquad (15.6)$$

Using the Δ_h symbol for the denominator, we have

$$V_{CE} = \frac{h_{ie}i_C - h_{fe}V_{BE}}{\Delta_h}$$

or

$$V_{CE}\Delta_h = h_{ie}i_C - h_{fe}V_{BE}$$

From the equivalent circuit (figure 15-4) we see

$$i_C = -\frac{V_{CE}}{R_L}$$

We may therefore write

$$V_{CE}\Delta_h = -\frac{h_{ie}V_{CE}}{R_L} - h_{fe}V_{BE}$$

Collecting V_{CE} terms on the left gives us

$$V_{CE}\Delta_h + V_{CE}\frac{h_{ie}}{R_L} = -h_{fe}V_{BE}$$

or

$$V_{CE}\left(\Delta_h + \frac{h_{ie}}{R_L}\right) = -h_{fe}V_{BE}$$

Therefore

$$A_v = \frac{V_{CE}}{V_{BE}} = \frac{-h_{fe}}{\Delta_h + h_{ie}/R_L}$$

And if we multiply both the numerator and denominator by R_L, we have

$$\boxed{A_v = \frac{-h_{fe}R_L}{h_{ie} + \Delta_h R_L}} \qquad (15.7a)$$

which is an h-parameter equation that can be used for finding the voltage gain of a common emitter transistor amplifier. When the hybrid-π equivalent is used, the voltage gain is simply

$$A_v = -g_m R_L \qquad (15.7b)$$

Actually this equation is appropriate only for the transistor itself. However, since from the original circuit we see that

$$e_{in} = V_{BE} \quad \text{and} \quad e_o = V_{CE}$$

then the whole circuit gain ($K_v = e_o/e_i$) is equal to the value given in equation 15.7.

$$\boxed{K_v = A_v} \qquad (15.8)$$

Power Gain. The power gain of an amplifier may be most easily found by determining A_i and A_v as described above and then using

$$\boxed{A_p = |A_i|\,|A_v|} \qquad (15.9)$$

And for the whole amplifier circuit:

$$\boxed{K_p = |K_i|\,|K_v|} \qquad (15.10)$$

Input Resistance. To solve for the amplifier's input resistance we start with equation 15.2.

$$i_C = h_{fe} i_B + h_{oe} V_{CE}$$

And since $i_C = -V_{CE}/R_L$, we may write

$$-\frac{V_{CE}}{R_L} = h_{fe} i_B + h_{oe} V_{CE}$$

or

$$\frac{V_{CE}}{R_L} + h_{oe} V_{CE} = -h_{fe} i_B$$

Factoring V_{CE} out of the lefthand terms

$$V_{CE}\left(\frac{1}{R_L} + h_{oe}\right) = -h_{fe} i_B$$

or

$$V_{CE} = \frac{-h_{fe} i_B}{\frac{1}{R_L} + h_{oe}}$$

Multiplying both denominator and numerator by R_L gives us

$$V_{CE} = \frac{-h_{fe} i_B R_L}{1 + h_{oe} R_L}$$

Substituting this relationship into equation 15.1 ($V_{BE} = h_{ie} i_B + h_{re} V_{CE}$) for V_{CE} renders

$$V_{BE} = h_{ie} i_B - \frac{h_{fe} h_{re} R_L}{1 + h_{oe} R_L} i_B$$

Then factoring i_B in the righthand terms

$$V_{BE} = i_B\left(h_{ie} - \frac{h_{fe} h_{re} R_L}{1 + h_{oe} R_L}\right)$$

or

$$R_i = \frac{V_{BE}}{i_B} = h_{ie} - \frac{h_{fe} h_{re} R_L}{1 + h_{oe} R_L}$$

Placing all of the right side terms over the common denominator gives us

$$R_i = \frac{h_{ie} + h_{ie} h_{oe} R_L - h_{fe} h_{re} R_L}{1 + h_{oe} R_L}$$

Factoring R_L from the two numerator terms gives

$$R_i = \frac{h_{ie} + (h_{ie} h_{oe} - h_{fe} h_{re})\, R_L}{1 + h_{oe} R_L}$$

Finally, we observe that the terms within the parentheses is the quantity previously called Δ_h. We may therefore write

$$R_i = \frac{h_{ie} + \Delta_h R_L}{1 + h_{oe} R_L} \qquad (15.11)$$

Using this h-parameter equation we may compute the input resistance of the common emitter amplifier. For the hybrid-π equivalent, R_i is equal to r_π.

As before, this equation applies only to the transistor itself, not to the amplifier as a whole.

In figure 15-5, we see that the input resistance of the whole circuit will be

$$\boxed{R_{in} = \frac{R_B R_i}{R_B + R_i}} \qquad (15.12)$$

Output Resistance. We may determine the value of the Thévenin's equivalent output impedance ($R_o = V_{CE}/i_C$) by starting with equation 15.1.

$$V_{BE} = h_{ie} i_B + h_{re} V_{CE} \qquad (15.1)$$

Observing from the hybrid equivalent circuit (figure 15-3) that if e_s is short-circuited, then

$$V_{BE} = -i_B R_S$$

Using this relationship in equation 15.1 we have

$$-i_B R_S = h_{ie} i_B + h_{re} V_{CE}$$

Collecting i_B terms on the lefthand side gives

$$-i_B R_S - h_{ie} i_B = h_{re} V_{CE}$$

or

$$i_B (R_S + h_{ie}) = -h_{re} V_{CE}$$

which may be rewritten in the form

$$i_B = -\frac{h_{re} V_{CE}}{h_{ie} + R_S}$$

Substituting this value of i_B into equation 15.2 ($i_C = h_{fe} i_B + h_{oe} V_{CE}$) gives us

$$i_C = h_{oe} V_{CE} - \frac{h_{fe} h_{re}}{h_{ie} + R_S} V_{CE}$$

Dividing both sides of the equation by V_{CE} renders

$$\frac{i_C}{V_{CE}} = h_{oe} - \frac{h_{fe} h_{re}}{h_{ie} + R_S}$$

Placing all of the righthand terms over the common denominator provides

$$\frac{i_C}{V_{CE}} = \frac{h_{ie} h_{oe} - h_{fe} h_{re} + h_{oe} R_S}{h_{ie} + R_S}$$

The first two numerator terms are the same as those we have been calling Δ_h. We may therefore write

$$\frac{i_C}{V_{CE}} = \frac{\Delta_h + h_{oe} R_S}{h_{ie} + R_S}$$

Finally, since R_o equals V_{CE}/i_C, we may take the reciprocal of each side and have

$$\boxed{R_o = \frac{h_{ie} + R_S}{\Delta_h + h_{oe} R_S}} \qquad (15.13)$$

which is the h-parameter equation we shall use in determining the value of R_o for the transistor alone. When using the hybrid-π equivalent we assume that R_o is so large that it can be ignored.

The output impedance of the entire stage (excluding the load resistor R) will be the parallel combination of R_C and R_o.

$$Z_o = \frac{R_C R_o}{R_C + R_o} \qquad (15.14)$$

For the hybrid-π circuit Z_o is approximately equal to R_C.

To use the equations developed for A_i, A_v, A_P, R_i and R_o, the values of the h parameters must be known. They may, of course, be determined from the input and output characteristics of the transistor.

In a practical situation, the problem is frequently the measurement of the circuit parameters rather than their calculation. At this point we shall turn our attention to techniques appropriate for carrying out these measurements.

Voltage Gain Measurement. The voltage gain of an amplifier may be readily measured using the circuit shown in figure 15-6. An appro-

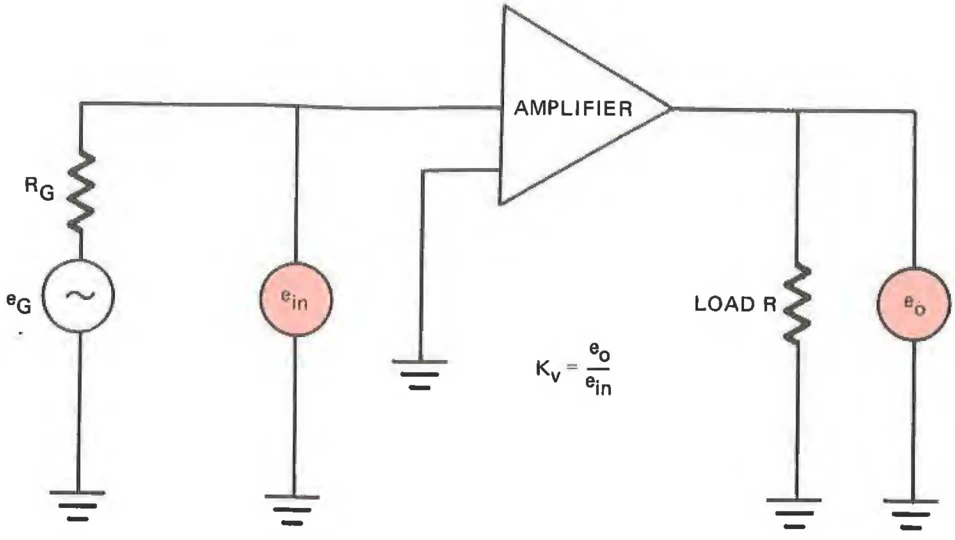


Fig. 15-6 Measuring Voltage Gain

priate signal is applied while the values of the input and output voltage are measured with voltmeters. The voltage gain is then

$$\boxed{K_v = \frac{e_o}{e_{in}}} \qquad (15.15)$$

Current Gain Measurement. In a practical situation it is normally the whole circuit current gain that is of interest. This quantity can readily be measured using a circuit of the type shown in figure 15-7. In this circuit the output current is

$$i_o = \frac{e_o}{R}$$

while the input current is

$$i_g = \frac{e_i}{R_i}$$

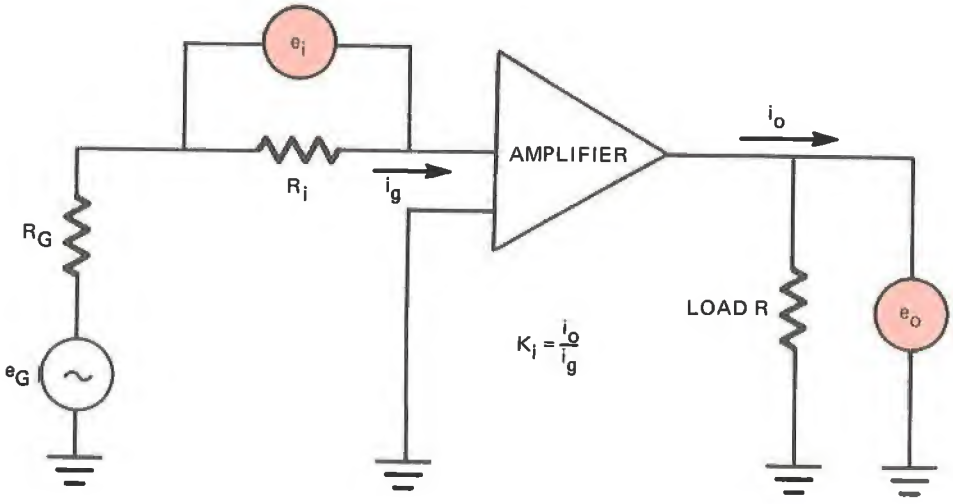


Fig. 15-7 Measuring Current Gain

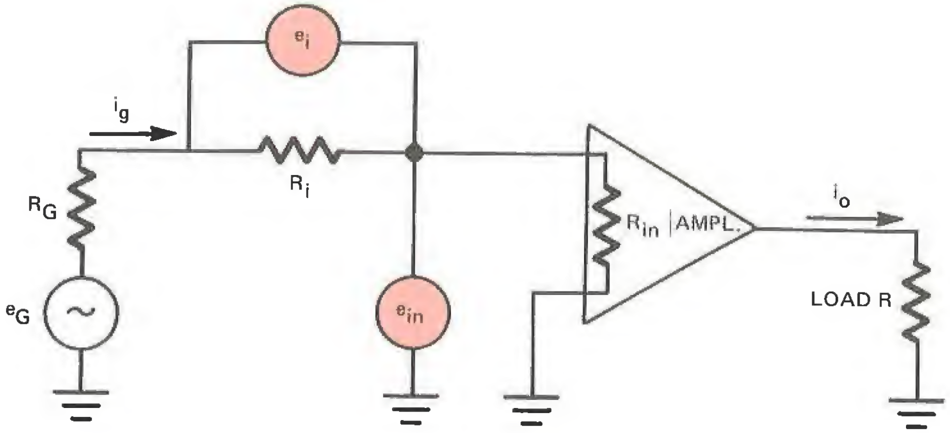


Fig. 15-8 Measuring Input Resistance

The current gain of the amplifier circuit is, therefore

$$\boxed{K_i = \frac{i_o}{i_g} = \frac{e_o R_i}{e_i R}} \qquad (15.16)$$

Input Resistance Measurement. The input resistance of an amplifier circuit can be determined in a number of ways. One of the ways is illustrated in figure 15-8. Since the same current (i_g) flows through both R_i and R_{in} (assuming the two voltmeters to be of very high resistance), we may write

$$\frac{e_i}{R_i} = \frac{e_{in}}{R_{in}}$$

or

$$\boxed{R_{in} = \frac{e_{in} R_i}{e_i}} \qquad (15.17)$$

Output Resistance Measurement. The measurement of the output resistance of an amplifier is slightly more involved than were the three previous measurements. It can, however, be carried out using a circuit such as the one shown in figure 15-9.

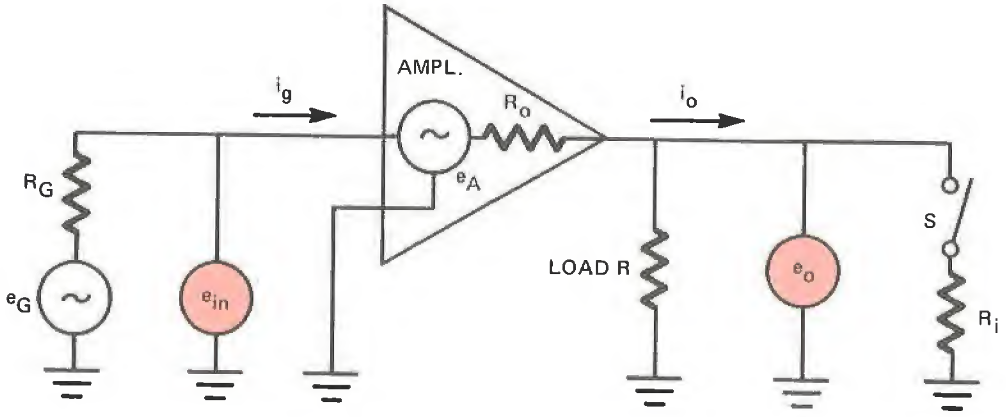


Fig. 15-9 Measuring Output Resistance

If the equivalent generator voltage e_A is held constant, then the output loop equation with only load R connected will be

$$e_A - i_oR_o - i_oR = 0$$

or

$$e_A = i_o(R_o + R)$$

And since $i_o = e_o/R$, we have

$$e_A = \frac{e_o}{R}(R_o + R)$$

Then if we connect load R_i in parallel with load R, the total load (R′) becomes

$$R' = \frac{RR_i}{R + R_i}$$

and the loop equation is now

$$e_A = \frac{e_o'}{R'}(R_o + R')$$

where e_o' is the new value of output voltage. Since e_A is held constant, we may equate the two equations for e_A

$$\frac{e_o}{R}(R_o + R) = \frac{e_o'}{R'}(R_o + R')$$

Solving this relationship for R_o renders

$$R_o = \frac{e_o - e_o'}{\left(\frac{e_o'}{R'} - \frac{e_o}{R}\right)} \qquad (15.18)$$

which allows us to determine R_o using the two load voltage measurements and the two load resistance values.

The value of R_i should be chosen to provide a change in output voltage of about 10 percent.

MATERIALS

1 2N1304 transistor (or equiv)
1 Set of transistor curves for the above
1 Transistor socket
1 Breadboard with clip terminals
1 47k resistor 1/2W
1 7.5k resistor 1/2W
2 2.2k resistors 1/2W
1 470-ohm resistor 1/2W
3 10-μF 50W VDC capacitors
1 Resistance substitution box (15-10 megohms 1/2W)
1 Variable DC power supply (0-40V)
1 Audio generator
2 VOMs or FEMs
1 Oscilloscope
1 220-ohm resistor 2W
1 1.8k ohm resistor 1/2W

PROCEDURE

1. Using the characteristic curves, determine the Q-point conditions for the circuit shown in figure 15-10. Record the values of V_{CE}, I_C, and I_B in the data table.
2. From the characteristic curves, determine the values of h_{ie}, h_{fe}, h_{re}, and h_{oe} in the vicinity of the Q-point. Record them in the data table.
3. Using the appropriate equations from the discussion, compute and record K_i, K_v, K_p, R_{in}, and R_o (assume $R_G \approx 200\Omega$).
4. Assemble the circuit neatly on a breadboard.

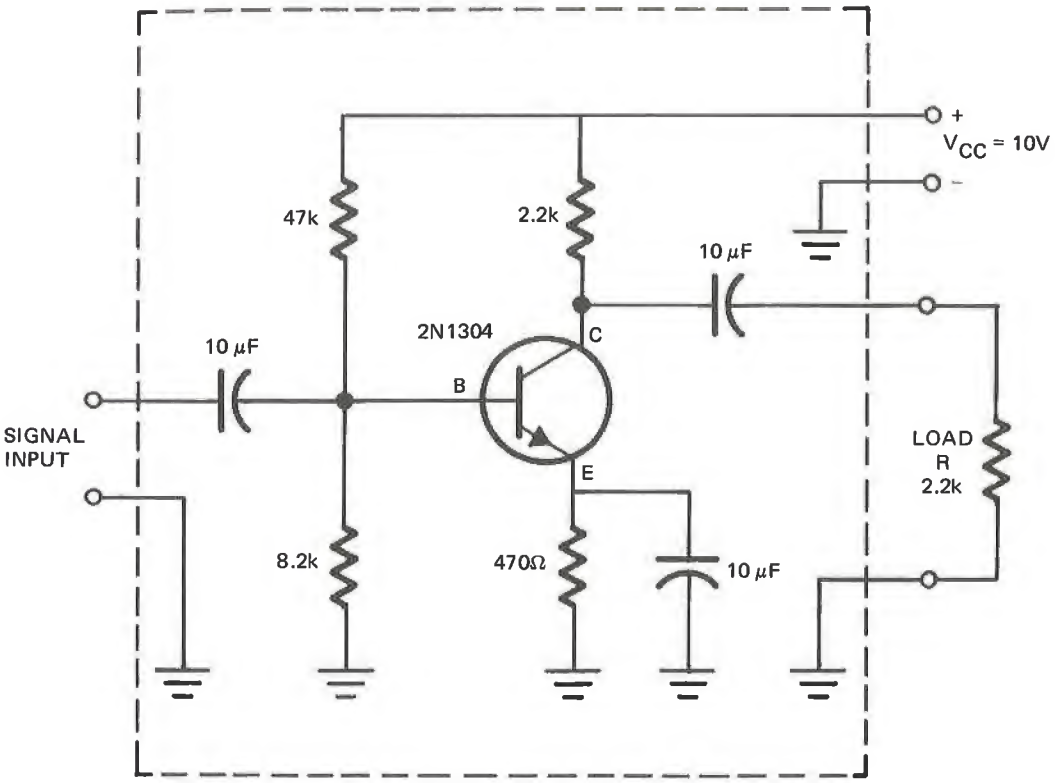


Fig. 15-10 The Experimental Circuit

5. Using a meter, measure and record the values of V_{CE}, I_C, and I_B.
6. Construct the audio generator circuit shown in figure 15-11.
7. Connect the audio signal to the input of the amplifier. Also connect the oscilloscope to the output of the amplifier in parallel with the 2.2k load resistor.
8. Adjust the output of the audio generator to a frequency of 1 kHz and a level well below that which produces a visibly distorted sinewave *at the amplifier output.*

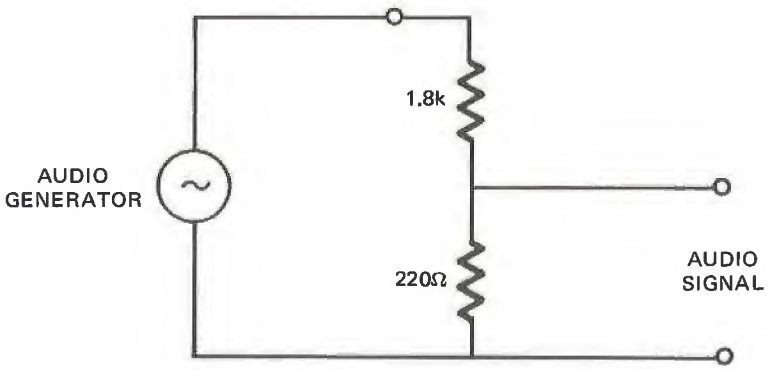


Fig. 15-11 Audio Generator with Voltage Divider

9. Record the peak-to-peak audio output voltage.
10. Move the oscilloscope to the amplifier input terminals and record the peak-to-peak audio input voltage.
11. Record the value of K_v thus measured.
12. Using the appropriate techniques and the resistance substitution box for R_i, measure and record K_i, K_p, R_{in} and R_o.

Qty	V_{CE}	I_C	I_B	h_{ie}	h_{fe}	h_{re}	h_{oe}	K_v	K_i	K_p	R_{in}	R_o
Computed Values												
Measured Values												

Fig. 15-12 The Data Table

ANALYSIS GUIDE. In analyzing the results of this experiment, you should consider the extent to which the computed values agreed with the measured ones. Explain any major disagreement between them.

PROBLEMS

1. If the value of h_{ie} for a particular transistor changed by 100 percent, how much would R_{in} change? Assume that all other quantities remained constant.
2. Will K_i always be greater or less than A_i? Why?
3. Is R_o a linear or nonlinear quantity? Why do you think so?

experiment 16 VACUUM TUBE AMPLIFIER SMALL-SIGNAL ANALYSIS

INTRODUCTION. The vacuum tube amplifier, while not the *most* popular circuit, is still found in some electronic applications. In this experiment we shall examine some of the more important vacuum tube amplifier parameters.

DISCUSSION. In this experiment we shall consider both triode and pentode amplifier circuits. Because it is slightly simpler (no screen grid current), the triode will be considered first.

Triode Amplifiers. A basic triode amplifier is shown in figure 16-1. The DC quiescent operating point is located using conventional loadline analysis techniques.

The AC characteristics of the amplifier can be examined using the equivalent circuit shown in figure 16-2.

If we assume that the grid current i_G is negligible, then the input resistance becomes equal to the value of the grid resistor (R_G).

$$\boxed{R_{in} = R_G} \tag{16.1}$$

In order to determine the value of the stage voltage gain, we must observe that the AC plate current is

$$i_P = \frac{\mu e_G}{r_p + R_L'}$$

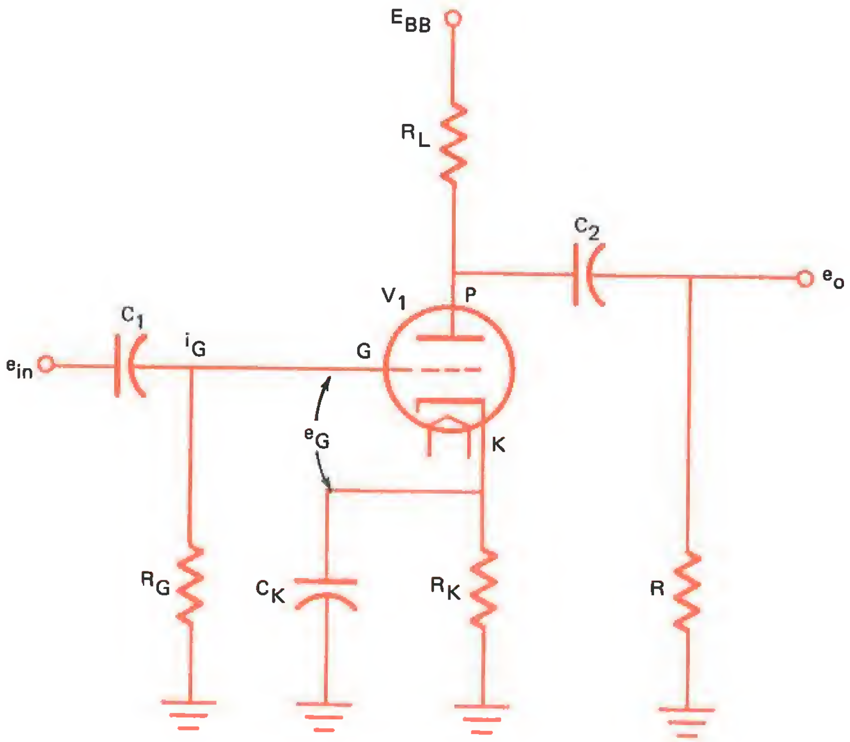


Fig. 16-1 A Basic Triode Amplifier Circuit

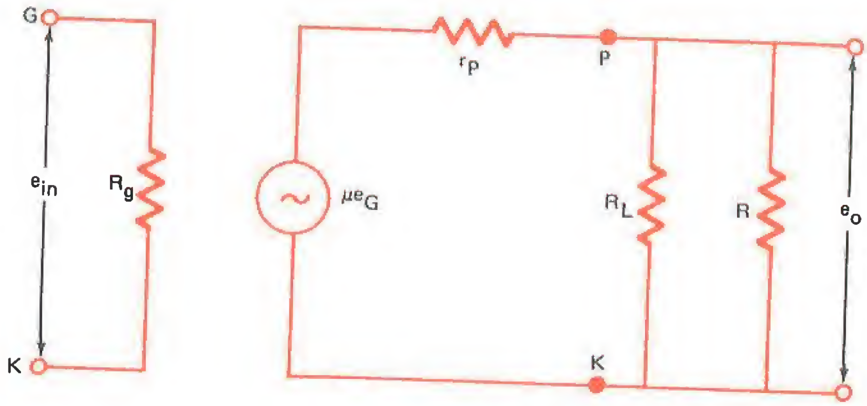


Fig. 16-2 Equivalent Circuit of a Triode Amplifier

where R'_L is the parallel combination of R_L and R.

$$R'_L = \frac{R_L R}{R_L + R}$$

Also, if the cathode is adequately bypassed by C_K ($Z_K \approx 0$ at the signal frequency), then e_G is equal to e_{in}. We may therefore rewrite the AC plate current equation as

$$i_P = \frac{\mu e_{in}}{r_P + R'_L}$$

From the equivalent circuit we can observe that the output voltage is

$$e_o = -i_P R'_L$$

Therefore

$$e_o = \frac{-\mu e_{in} R'_L}{r_P + R'_L}$$

And since the overall voltage gain is defined as

$$\boxed{K_v = \frac{e_o}{e_{in}}} \qquad (16.2)$$

we now have

$$\boxed{K_v = \frac{-\mu R'_L}{r_P + R'_L}} \qquad (16.3)$$

as the voltage gain of the triode amplifier.

The current gain of a vacuum tube amplifier is of only casual interest because the tube does not respond to current inputs. We can, however, determine it by noting that the input current is

$$i_{in} = \frac{e_{in}}{R_g}$$

while the output load current is

$$i_o = e_o/R$$

The current gain is then

$$\boxed{K_i = \frac{i_o}{i_{in}} = \frac{e_o}{e_{in}}\left(\frac{R_G}{R}\right) = -K_v\left(\frac{R_G}{R}\right)} \qquad (16.4)$$

In like manner, the power gain of a vacuum tube amplifier is frequently of little interest. It may be determined, however, in the usual way:

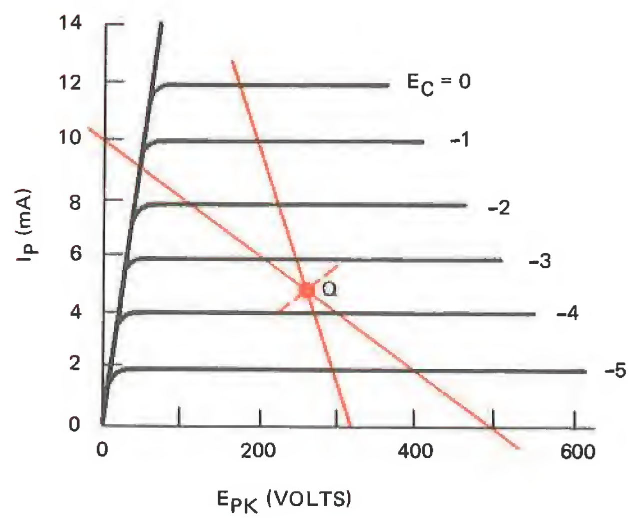
$$\boxed{K_p = |K_i|\,|K_v|} \qquad (16.5)$$

The output resistance (R_o) of the triode stage (Thèvenin's equivalent resistance) can be determined by removing the load resistor (R in figure 16-2) and examining the remaining resistance between the output terminals. When this is done, we see that R_o is simply R_L and r_p in parallel.

$$\boxed{R_o = \frac{R_L r_p}{R_L + r_p}} \qquad (16.6)$$

Pentode Amplifiers. In the case of a triode tube, the output characteristics are similar to those of a constant voltage source (a small change in e_p produces a relatively large change in i_p). Hence, we usually see a constant voltage equivalent circuit to represent a triode.

From the output characteristics of a pentode tube we see that even relatively large changes in e_p produce only small changes in i_p (figure 16-3). As a result, we usually



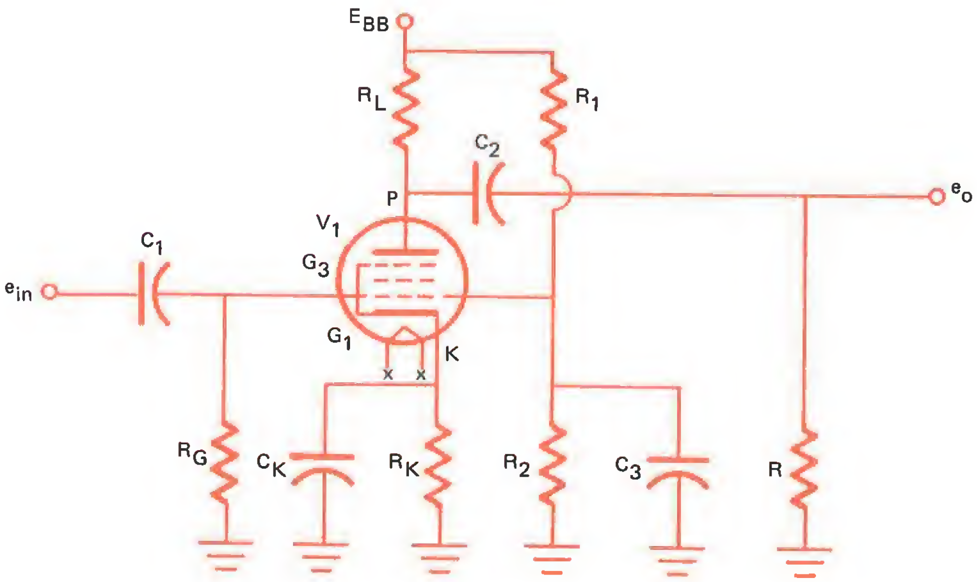


Fig. 16-3 A Typical Pentode Amplifier

use a constant current equivalent circuit to represent a pentode amplifier. We can arrive at the pentode equivalent circuit by Nortonizing the circuit given in figure 16-2. To do this we short circuit the output terminals and compute the circuit current,

$$i_P = \frac{e}{R} = \frac{\mu e_G}{r_P}$$

and since μ/r_P is equal to g_m, we may write

$$i_P = g_m e_G$$

Then because r_p is the internal resistance of the tube, we may draw the constant current equivalent circuit shown in figure 16-4. This circuit, of course, only applies for AC quantities. The DC parameters are found using conventional loadline techniques.

From this equivalent circuit we see that

$$\boxed{R_{in} = R_G} \qquad (16.1)$$

if i_G is zero as was the case for a triode.

Similarly, if the load (R) is removed, then the output resistance is

$$\boxed{R_o = \frac{R_L r_P}{R_L + r_P}} \qquad (16.6)$$

which is also identical to the triode case.

The output current (i_o through load R) will be

$$i_o = g_m e_G \frac{R_o}{R_o + R}$$

And the current gain becomes

$$\boxed{K_i = \frac{i_o}{i_{in}} = \frac{g_m R_o R_G}{R_o + R}} \qquad (16.7)$$

if e_G is equal to e_{in}, as is the case when the cathode is effectively bypassed by C_K.

The power gain may be determined as before with

$$\boxed{K_P = |K_i|\ |K_v|} \qquad (16.5)$$

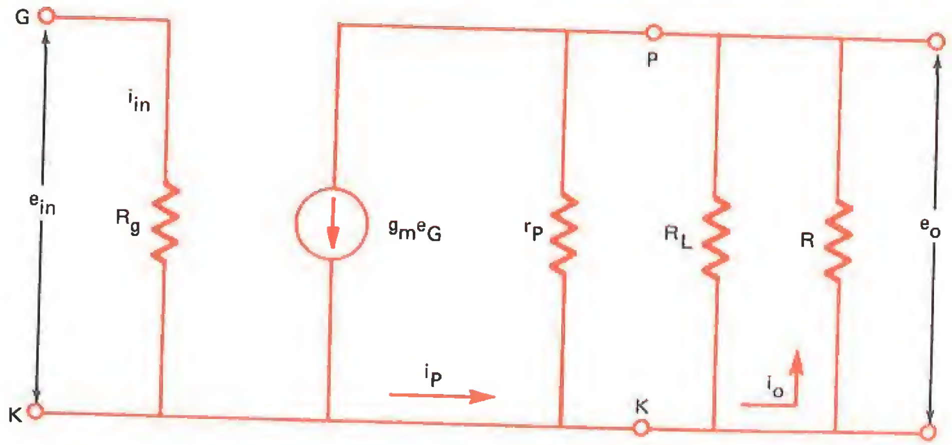


Fig. 16-4 The Pentode Equivalent Circuit

Finally, the voltage gain can be found by recognizing that

$$e_o = -i_o R = -g_m e_G \frac{R_o R}{R_o + R}$$

And the voltage gain is

$$\boxed{K_v = \frac{e_o}{e_{in}} = -g_m \frac{R_o R}{R_o + R}} \qquad (16.8)$$

when $e_G = e_{in}$

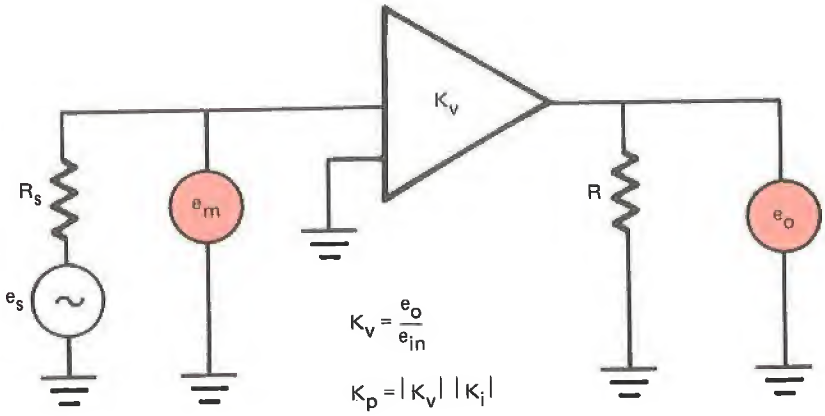
One special case is of interest. If the value of R_o is much larger than R, then the denominator in equation 16.8 may be reduced to R_o.

$$R_o + R \approx R_o \text{ if } R_o >> R$$

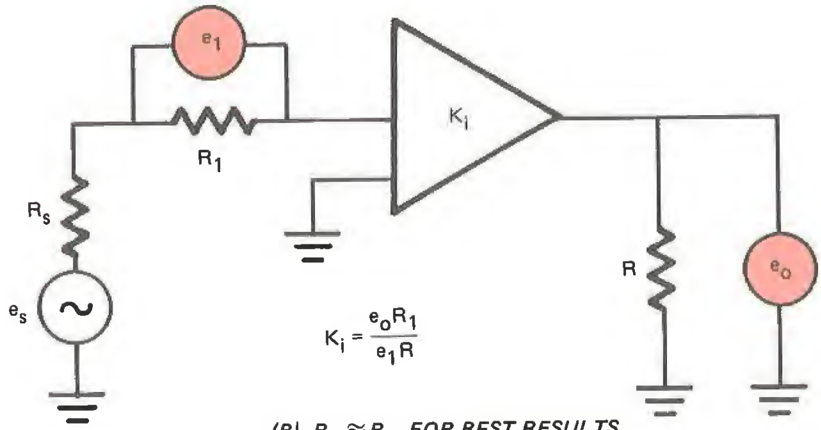
and the voltage gain becomes

$$\boxed{K_v \approx -g_m R} \qquad (16.9)$$

Vacuum Tube Amplifier Measurements. As is the case with other amplifiers, the five basic circuit parameters (K_v, K_i, K_p, R_{in}, and R_o) may be measured using the arrangements shown in figure 16-5.

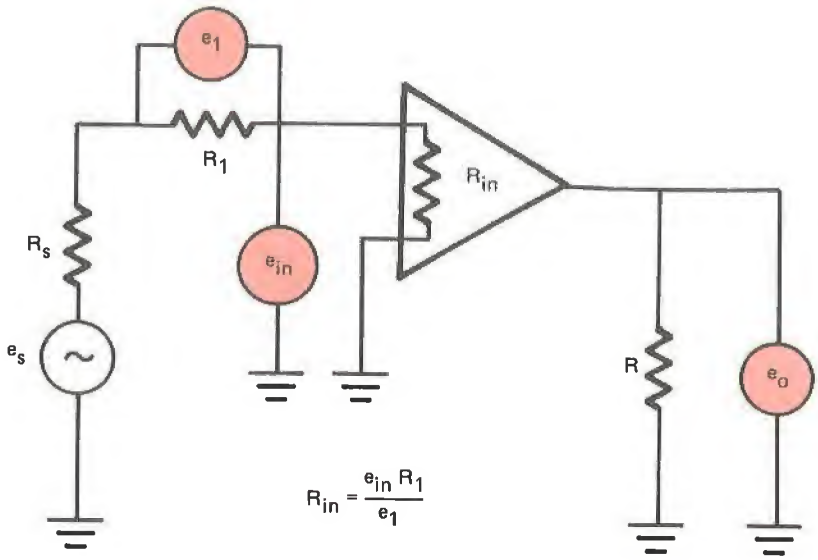


(A)



(B) $R_1 \approx R_{in}$ FOR BEST RESULTS

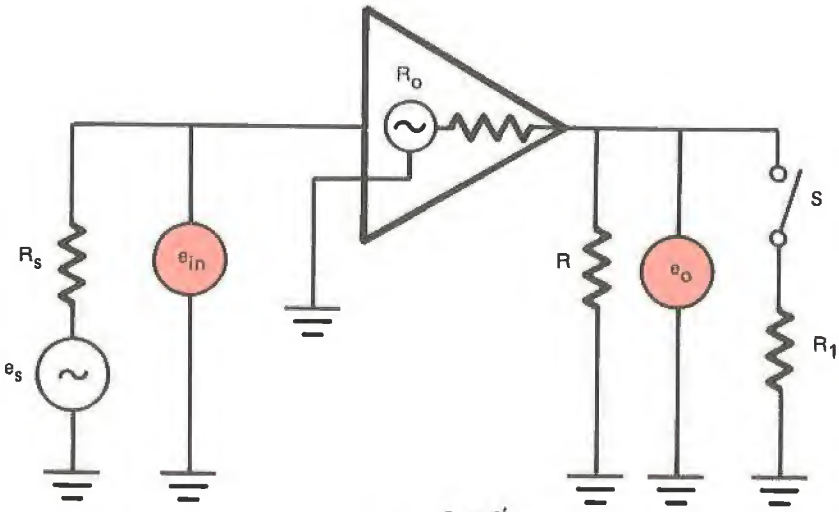
Fig. 16-5 Measuring Amplifier Parameters



$$R_{in} = \frac{e_{in} R_1}{e_1}$$

(C) $R_1 \approx R_{in}$ FOR BEST RESULTS

e_o = CONSTANT FOR BEST RESULTS



(D) $$R_o = \frac{e_o - e'_o}{\left(\frac{e'_o}{R'} - \frac{e_o}{R}\right)}$$

e_{in} = constant $R' = \dfrac{RR_1}{R + R_1}$

e'_o is e_o with R' connected

$e'_o \approx 0.9\, e_o$ for best results

Fig. 16-5 Measuring Amplifier Parameters (Cont'd)

MATERIALS

1 Vacuum tube 6AU8 or equivalent
1 Complete set of output characteristics
1 9 pin miniature tube socket
1 Breadboard
1 7.5k resistor 1/2W
1 10k resistor 1/2W
1 150Ω resistor 1/2W
1 300k resistor 1/2W
1 10 μF, 50W VDC capacitor
2 0.1 μF, 600W VDC capacitors
1 Audio generator
1 Resistance substitution box (15-10 megohm 1/2W)
1 Oscilloscope
2 VOM or FEM
1 Variable DC power supply (0–400V)
1 1.8k resistor 1/2W
1 220Ω resistor 2W

PROCEDURE

1. On the triode characteristic curves, locate the quiescent operating point for the circuit shown in figure 16-6. Record the values of E_C, E_P, and I_P.

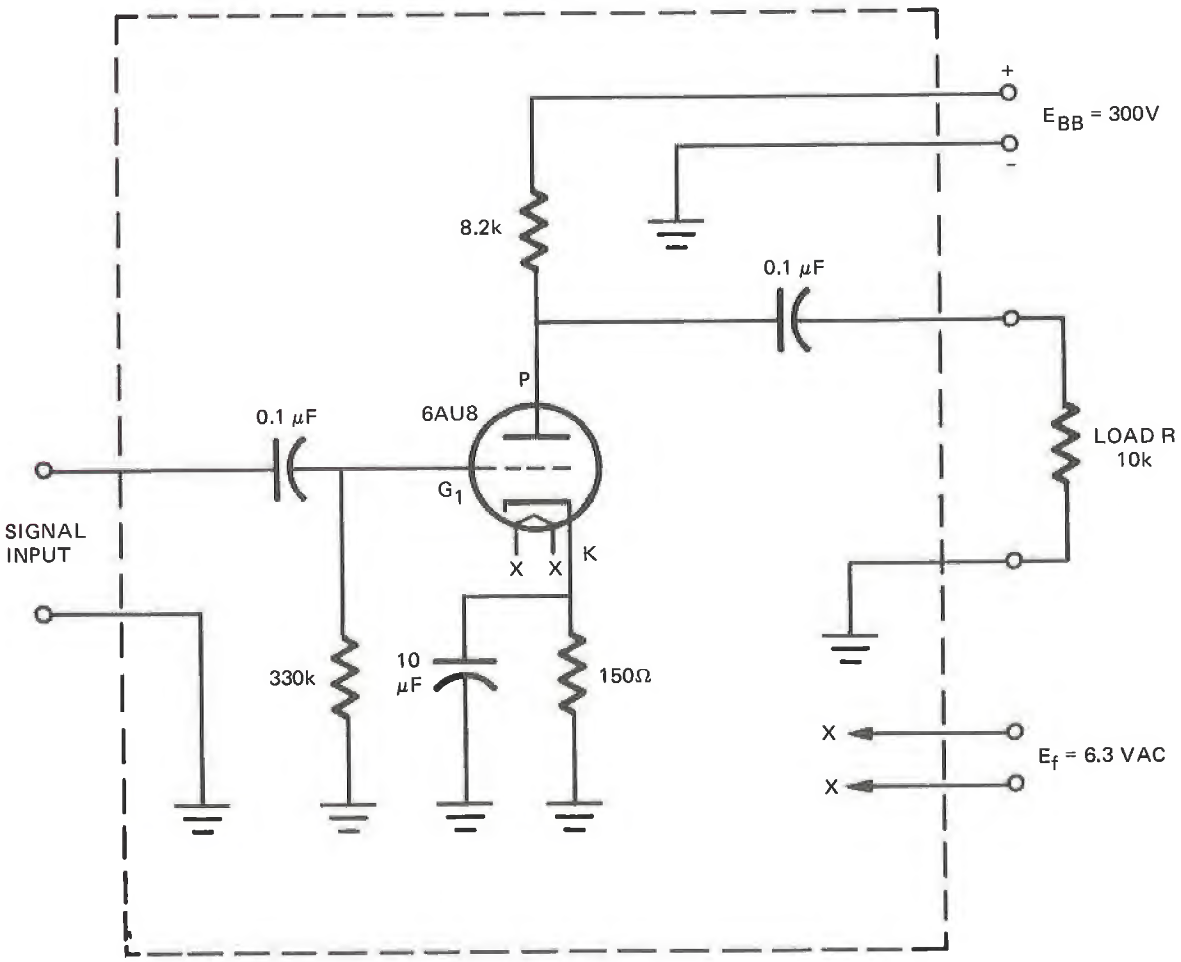


Fig. 16-6 The Experimental Amplifier

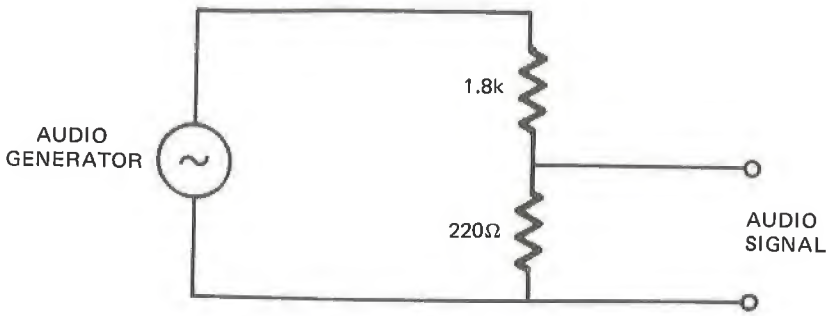


Fig. 16-7 Audio Generator and Voltage Divider

2. Using the characteristic curves, determine the values of μ, g_m, and r_P in the vicinity of the Q-point. Record these values in the data table.
3. Select the appropriate equations and compute the values of K_v, K_i, K_p, R_{in}, and R_o.
4. Assemble the circuit neatly on a breadboard.
5. Measure and record the values of E_C, E_P, and I_P.
6. Connect the oscilloscope across the 10k load resistor.
7. Assemble the audio generator and voltage divider shown in figure 16-7. Set the audio generator to a frequency of 1 kHz.
8. Connect the audio signal from the voltage divider to the amplifier signal input. Set the level of the generator for a small *undistorted* sinewave at the amplifier output.
9. Using the resistance substitution box for R_1 and the appropriate techniques, measure and record K_v, K_i, K_p, R_{in}, and R_o.

Quantity	E_C	E_P	I_P	μ	g_m	r_P
Computed Values						
Measured Values						

Quantity	K_v	K_i	K_P	R_{in}	R_o
Computed Values					
Measured Values					

Fig. 16-8 The Data Table

ANALYSIS GUIDE. The objective of this experiment has been to examine the parameters of a vacuum tube amplifier. In analyzing these data you should consider the extent to which the computed values agreed with the measured quantities. In particular, you should explian any major diagreements.

PROBLEMS

1. Using the 6AU8 pentode curves, repeat experimental steps 1, 2, and 3 for the circuit shown in figure 16-9.

2. If an input of 0.5 sin 1256t volts is applied, what will be:
   a) the output voltage across the 1-megohm load?
   b) the AC plate current?

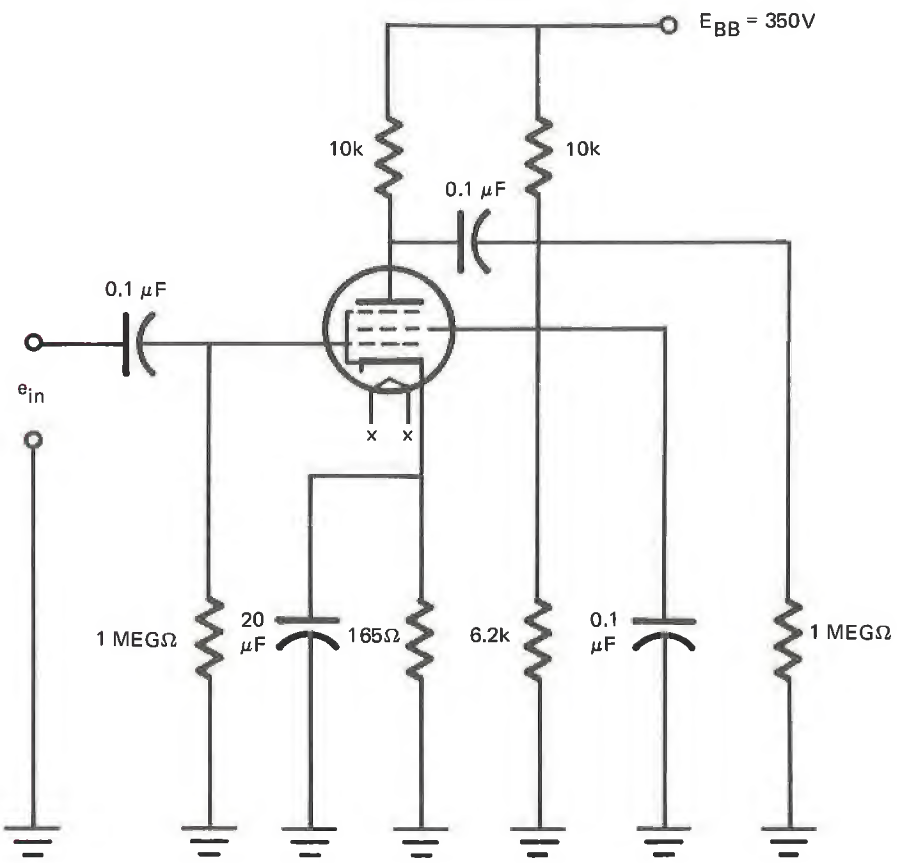


Fig. 16-9 Circuit for Problem One

experiment **17** *FET AMPLIFIER SMALL-SIGNAL ANALYSIS*

INTRODUCTION. In recent years the field effect transistor has become one of the most important electronic amplifying devices. In this experiment, we shall examine the small-signal parameters of a typical common source FET amplifier.

DISCUSSION. The AC drain current which flows in a field effect transistor is governed by the equation

$$\boxed{i_D = g_m V_{GS} + \frac{V_{DS}}{r_D}} \tag{17.1}$$

If we multiply each term by the value of r_D we have

$$i_D r_D = g_m r_D V_{DS} + V_{DS}$$

Recognizing that $g_m r_D = \mu$ and rearranging the expression, we have

$$\mu V_{GS} - i_D r_D + V_{DS} = 0$$

We may interpret this relationship as being the output loop equation for the FET. A circuit which would produce this equation is shown in figure 17-1.

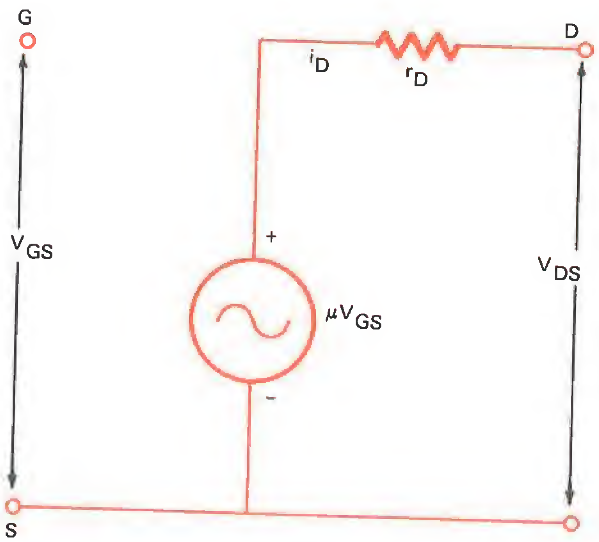


Fig. 17-1 Equivalent Circuit of an FET

If we connect the FET into a common source amplifier circuit such as the one shown in figure 17-2, we find that its output characteristics are of the constant current type. That is, a large change in V_{DS} produces only a small change in i_D if V_{GS} is constant.

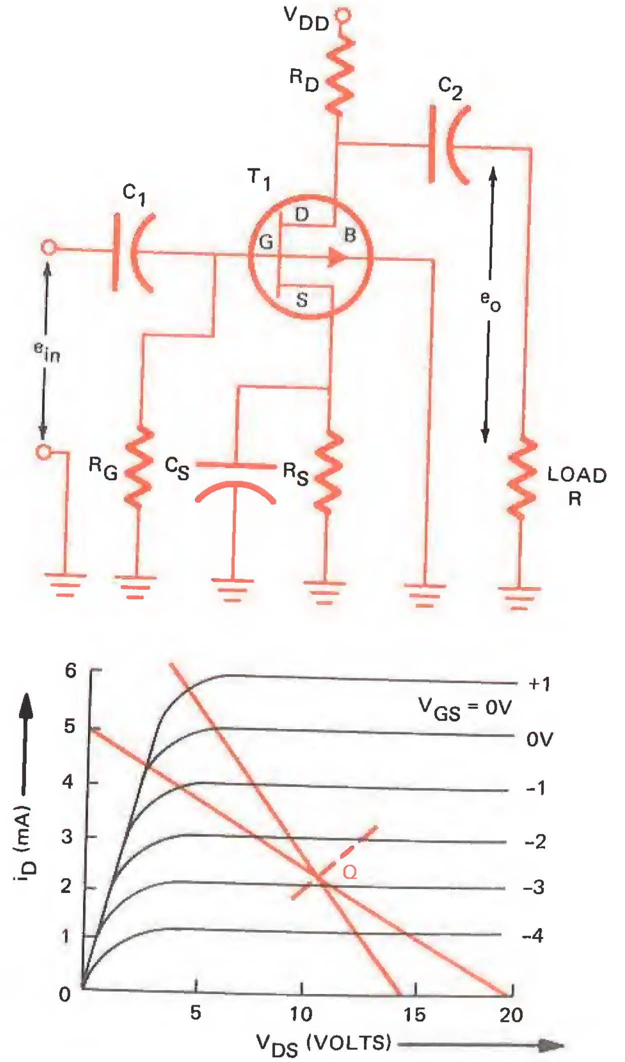


Fig. 17-2 FET Amplifier and Characteristics

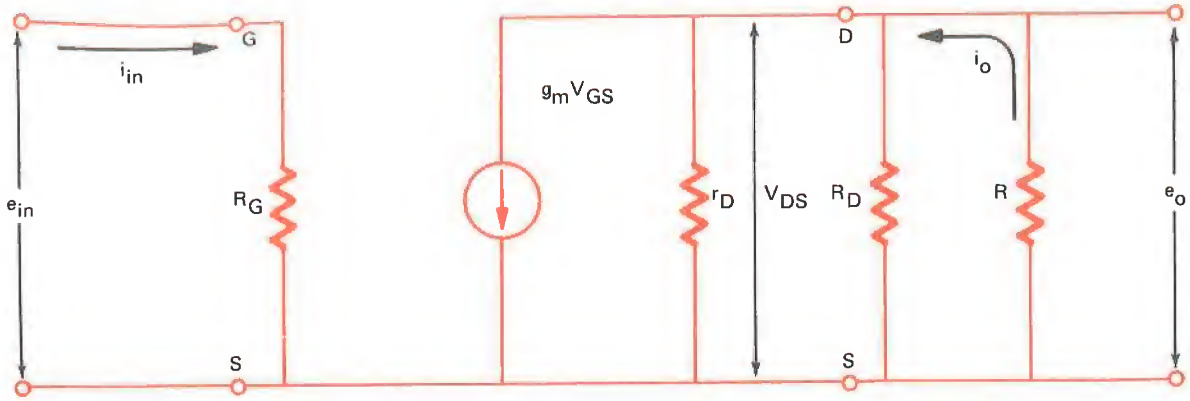


Fig. 17-3 Constant Current Equivalent of an FET Amplifier

Because of the constant current nature of the FET characteristics it is probably more convenient to use a constant current equivalent circuit based on equation 17.1 such as the one shown in figure 17-3.

In a practical case we must determine the quiescent operating condition using conventional loadline analysis techniques. Then we determine g_m and r_D in the vicinity of the Q-point. When these things are done, we may use the equivalent circuit shown in figure 17-3 to determine the amplifier's parameters.

Input Resistance. Since the input current of an FET is very small, we normally assume that the input resistance of the amplifiers is equal to R_G:

$$\boxed{R_{in} = R_G} \tag{17.2}$$

Output Resistance. If we disconnect the load resistor (R) in figure 17-3, we see that the output resistance (R_o) is the parallel combination of r_D and R_D. That is

$$\boxed{R_o = \frac{r_D R_D}{r_D + R_D}} \tag{17.3}$$

Redrawing the equivalent circuit to show R_o we have the circuit shown in figure 17-4.

Current Gain. Using this simplified equivalent circuit we observe that the output current (i_o) is

$$i_o = g_m V_{GS} \frac{R_o}{R_o + R} = g_m e_{in} \frac{R_o}{R_o + R}$$

while the input current has a value of

$$i_{in} = \frac{e_{in}}{R_G}$$

Consequently, we have, for the current gain of the stage

$$\boxed{K_i = \frac{i_o}{i_{in}} = g_m \frac{R_o R_G}{R_o + R}} \tag{17.4}$$

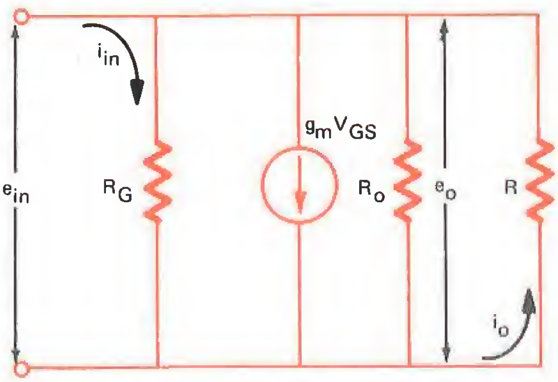


Fig. 17-4 The Simplified Equivalent Circuit

Voltage Gain. With the value of output current known we may readily determine the value of the output voltage,

$$e_o = -i_o R = g_m\, e_{in} \frac{R_o R_G}{R_o + R}$$

from which we see that the voltage gain is

$$K_v = \frac{e_o}{e_{in}} = g_m \frac{R_o R}{R_o + R} \qquad \textbf{(17.5)}$$

And if $R_o >> R$, then $R_o + R \approx R_o$, therefore

$$\boxed{K_v \approx g_m R}$$

is a useful approximation of voltage gain.

Is is perhaps worth noting at this point that the current and voltage gains are related by

$$K_i = -K_v \left(\frac{R_G}{R}\right) \qquad \textbf{(17.6)}$$

This fact becomes apparent when equations 17.4 and 17.5 are compared to each other.

Power Gain. As in the case of any other amplifier the power gain of the stage can be found using

$$\boxed{K_p = |K_i|\,|K_v|} \qquad \textbf{(17.7)}$$

FET AMPLIFIER MEASUREMENTS. The basic amplifier parameters discussed above can easily be measured using the circuits shown in figure 17.5.

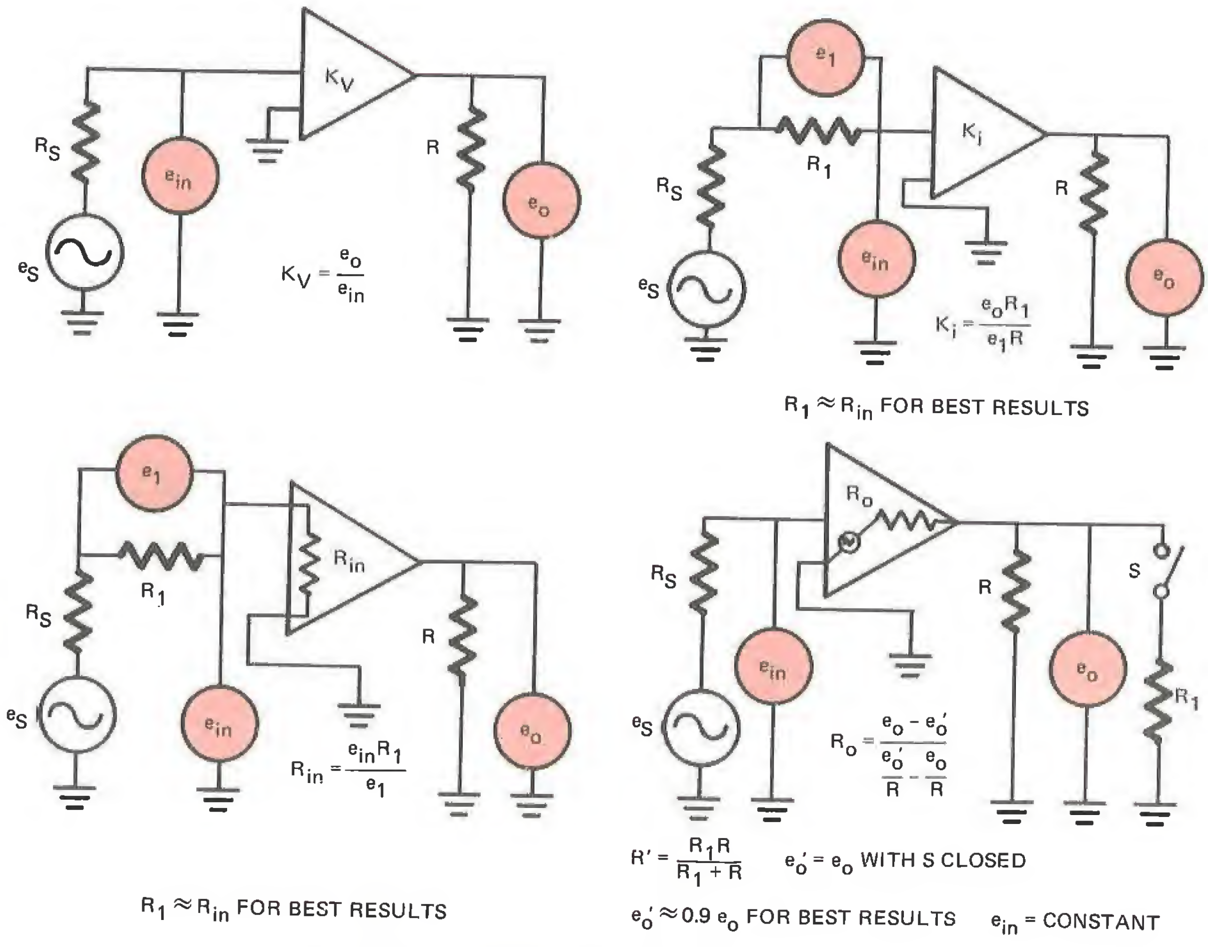


Fig. 17-5 Amplifier Parameter Measurements

MATERIALS

1 MOSFET type 40468 or equivalent
1 Set characteristic curves for the above device
1 Transistor socket
1 Breadboard
1 0.1 μF capacitor 600W VDC
2 10 μF capacitors 50W VDC
1 320k resistor (100K + 220K) 1/2W
1 1.8k resistor 1/2W
2 200Ω resistors 2W
1 Variable DC power supply (0 – 40V)
1 Oscilloscope
1 Audio generator
2 VOM or FEM
1 Resistance substitution box
(15 - 10 megohm 1/2W)

PROCEDURE

1. Using the output characteristics of the FET, determine the quiescent operating conditions for the circuit shown in figure 17-6. Record values for V_{DS}, V_{GS}, and I_D.
2. From the curves determine the values of μ, g_m, and r_D in the vicinity of the Q-point. Record these values.
3. With the appropriate relationships, compute and record values for K_v, K_i, K_p, R_{in}, and R_o.
4. Construct the circuit neatly on a breadboard.
5. Measure and record the values of V_{DS}, V_{GS}, and I_D.

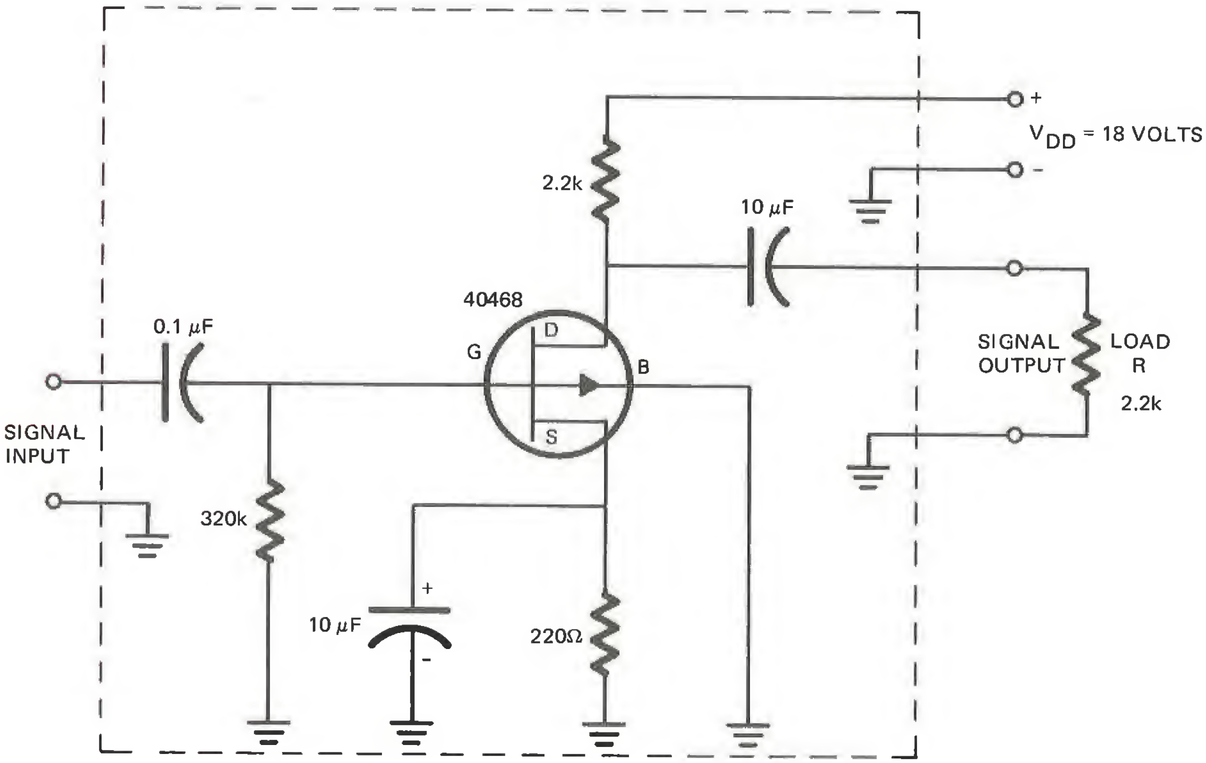


Fig. 17-6 The Experimental Amplifier

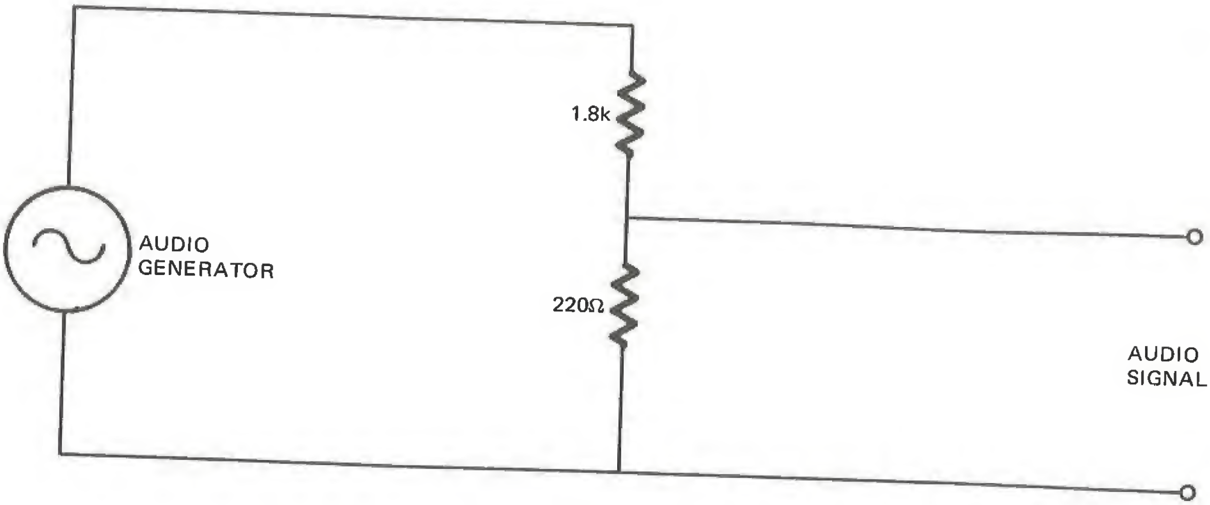


Fig. 17-7 The Audio Generator and Voltage Divider

6. Connect the oscilloscope across the 2.2k ohm load resistor.
7. Assemble the audio generator and voltage divider shown in figure 17-7.
8. Connect the audio signal from the voltage divider to the input of the amplifier, set the generator frequency to 1kHz and the level for a small *undistorted* sinewave at the amplifier output.
9. Measure the peak-to-peak value of the output signal (e_o).
10. Move the oscilloscope to the amplifier input and measure the peak-to-peak value of the input signal. Compute and record the measured value of K_v.
11. In a similar manner measure and record K_i, K_P, R_{in}, and R_o. (Use the resistance substitution box for R_i as needed.)

ANALYSIS GUIDE. In this experiment we have computed (using curves and equations) the values of gains and resistances for an FET circuit. We have also measured these same values. In your analysis you should consider the extent to which the calculations accurately predicted actual performance. In particular you should explain any major inaccuracies.

QTY	V_{DS}	V_{GS}	I_D	μ	g_m	r_D	K_v	K_i	K_P	R_{in}	R_o
Computed Values											
Measured Values				X	X	X					

Fig. 17-8 The Data Table

PROBLEMS

1. A certain FET has a g_m of 1000μ mhos and an r_D of 8K. What would be the values of K_v and R_o if this device were used in the experimental circuit?
2. Make a sketch of K_v versus R (the circuit load) for the amplifier used in the experiment.
3. Does the value of R_o depend in any way on the value of R? Explain your answer in detail.

experiment 18 AMPLIFIER COUPLING NETWORKS

INTRODUCTION. In many practical cases a single amplifier stage cannot provide the required gain from input to output. In such a case it is common practice to couple two or more amplifier stages together. In this experiment we shall examine several methods of accomplishing such a coupling.

DISCUSSION. As mentioned in the introduction, it is frequently necessary to couple two (or more) amplifier stages together to achieve a desired result. Figure 18-1 shows two amplifier stages and three basic types of coupling networks.

In each type (input, interstage, or output) the coupling network must effectively convey the desired signal from its input to its output. Under ideal conditions this would be accomplished without the loss of any energy. In practical situations such *lossless* coupling is rarely possible.

In addition to conveying the desired signal from circuit to circuit the coupling network may do one or more of the following:

1. *Change the level of signal*
2. *Block undesired signal frequencies*
3. *Limit the signal amplitude*
4. *Serve as an impedance matching device*
5. *Change the phase angle of the signal*
6. *Delay the signal by a specified length of time*
7. *Change the frequency of the signal*
8. *Add or remove signal information or perform any other specialized service required.*

Because a comprehensive study of coupling networks is of necessity very broad in scope, we shall limit this experiment to only the most common circuits.

Untuned (nonresonant) amplifiers employ three basic methods of coupling. These basic methods are:

1. **Resistance-Capacitance (RC) coupling.**
2. **Transformer coupling.**
3. **Direct current (DC) coupling.**

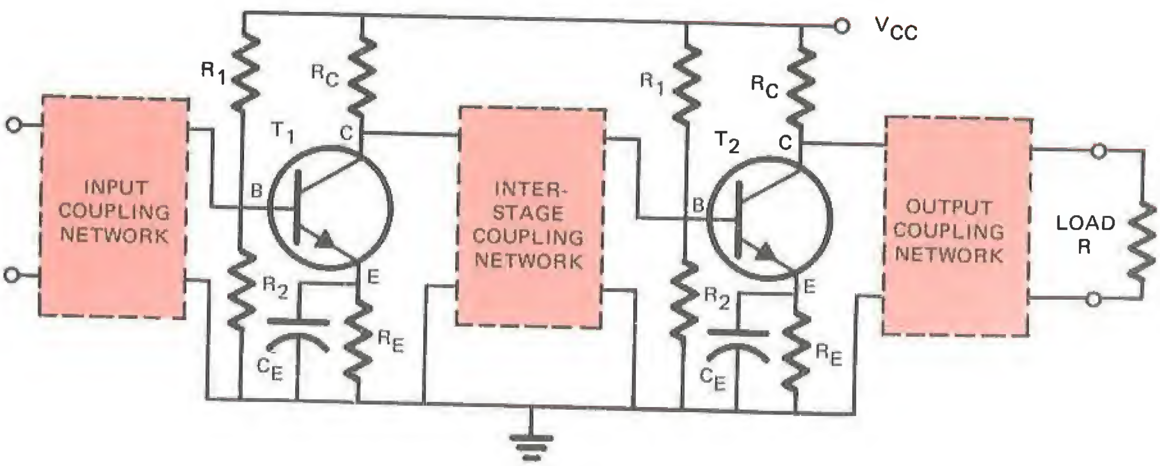


Fig. 18-1 The Three Basic Types of Coupling Networks

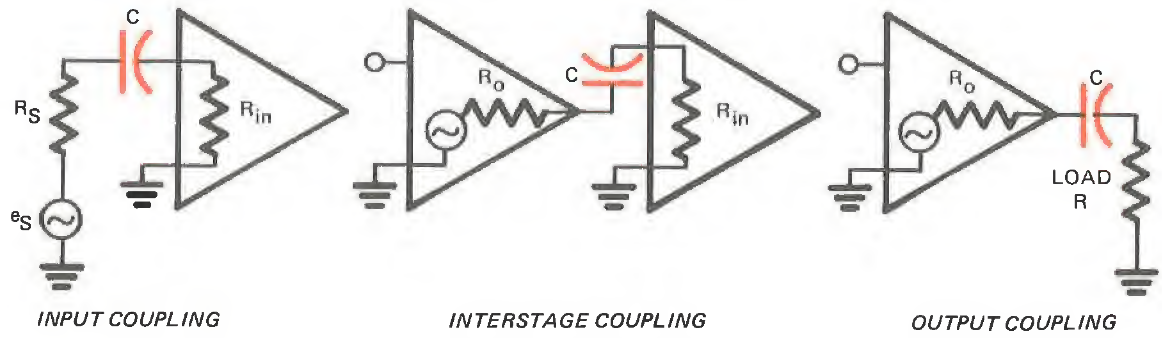


Fig. 18-2 RC Coupling Circuits

We shall consider each of these briefly.

RC Coupling: This type is one of the most frequently encountered basic coupling methods. When it is used the output resistance of the driving circuit is coupled through a capacitor to the input resistance of the driven circuit. Figure 18-2 shows typical examples of such circuits.

RC coupling is used when economy is an important factor and the goal is to couple AC signals while blocking any DC component. Notice that if impedance matching is important then it must be accomplished by adjusting R_o (or R_S) and R_{in} (or R). The value of the capacitor C is chosen such that

$$\boxed{X_C \ll R_{in} \text{ (or R)}} \qquad (18.1)$$

at the lowest frequency to be coupled.

Transformer Coupling: When AC signals are to be coupled and any DC component blocked *while effecting an impedance match,* transformers may be used. Figure 18-3

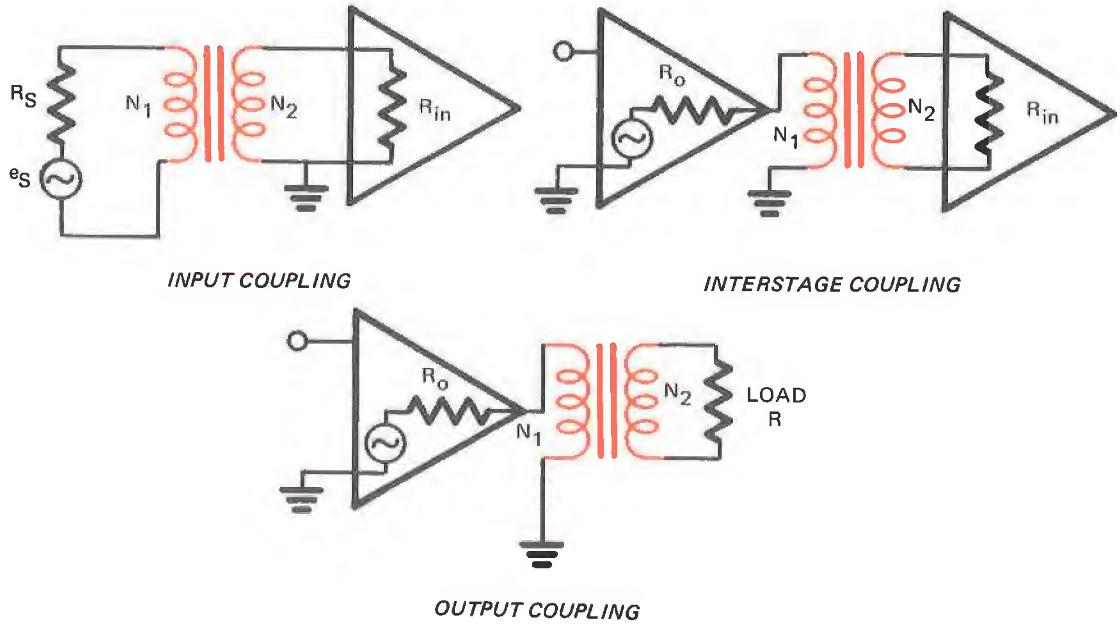


Fig. 18-3 Transformer-Coupled Circuits

shows typical examples of transformer-coupled circuits.

As stated before, transformers are normally used when impedance matching is important as would be the case in a current amplifier or power amplifier. The transformer turns ratio is normally chosen according to

$$\boxed{\frac{R_o}{R_{in}} = \left(\frac{N_1}{N_2}\right)^2} \qquad (18.2)$$

when an impedance match is desired.

Transformer coupling is also frequently used when:

1. A signal phase reversal is desired (the windings of the transformer may be reversed to effect 180° phase shift),
2. The driving circuit and driven circuit *do not* have common ground connections.

Direct Current Coupling: DC coupling is used when the signal frequency is near zero (direct current) or when the DC component can be used to establish the desired quiescent conditions in the driven stage.

There are many ways in which direct coupling may be achieved. Figure 18-4 shows only a few popular ones. The source is coupled to T_1 using a single series resistor to limit the base current. T_1 is coupled very directly to T_2 such that the collector voltage of T_1 is equal to the base voltage of T_2. T_2 couples the signal to T_3 through a breakdown diode (D_1) which causes a fixed reduction in voltage. T_3 is coupled to T_4 through the resistive voltage divider R_2 and R_3. By adjusting the values of the resistors, the base voltage of T_4 may be set at any point between $-V_{BB}$ and the positive collector voltage of T_3. Finally, T_4 is coupled directly to the load R.

In summary we should note that there are three basic coupling methods: RC, transformer and direct coupling. All are used in practical circuits and more than one method may be used in a single application.

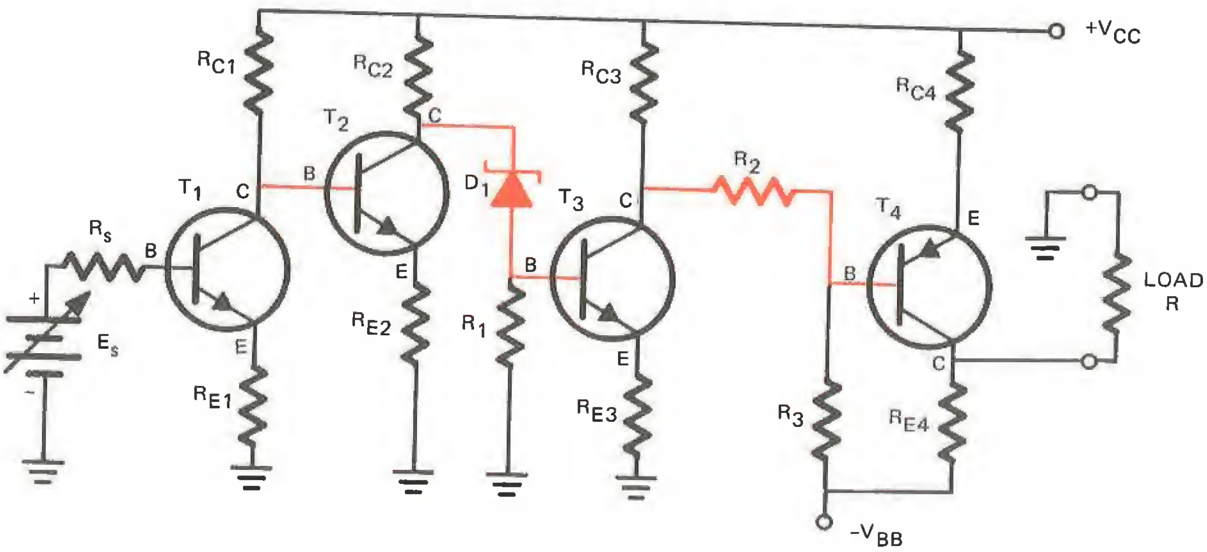


Fig. 18-4 Various Direct Coupling Methods

MATERIALS

1 Transistor type 2N1304 or equivalent
1 FET type 40468 or equivalent
1 Set of curves for the above
2 Transistor sockets
1 Breadboard
3 10 μF capacitors 50W VDC
1 1 meg resistor 1/2W
1 100k resistor 1/2W
1 68k resistor 1/2W
1 7.5k resistor 1/2W
2 2.2k resistors 1/2W
1 1k resistor 1/2W
1 470Ω resistor 1/2W
1 220Ω resistor 2W
1 VOM or FEM
1 Oscilloscope
1 Audio generator
1 Variable DC power supply (0–40V)
1 Capacitor substitution box (0.0001 -1.0 μF 600W VDC)
1 Sheet of graph paper

PROCEDURE

1. Using the characteristic curves determine the quiescent operating conditions for both of the amplifiers shown in figure 18-5. V_{DS}, V_{GS}, V_{CE}, and V_{BE} in the data table.

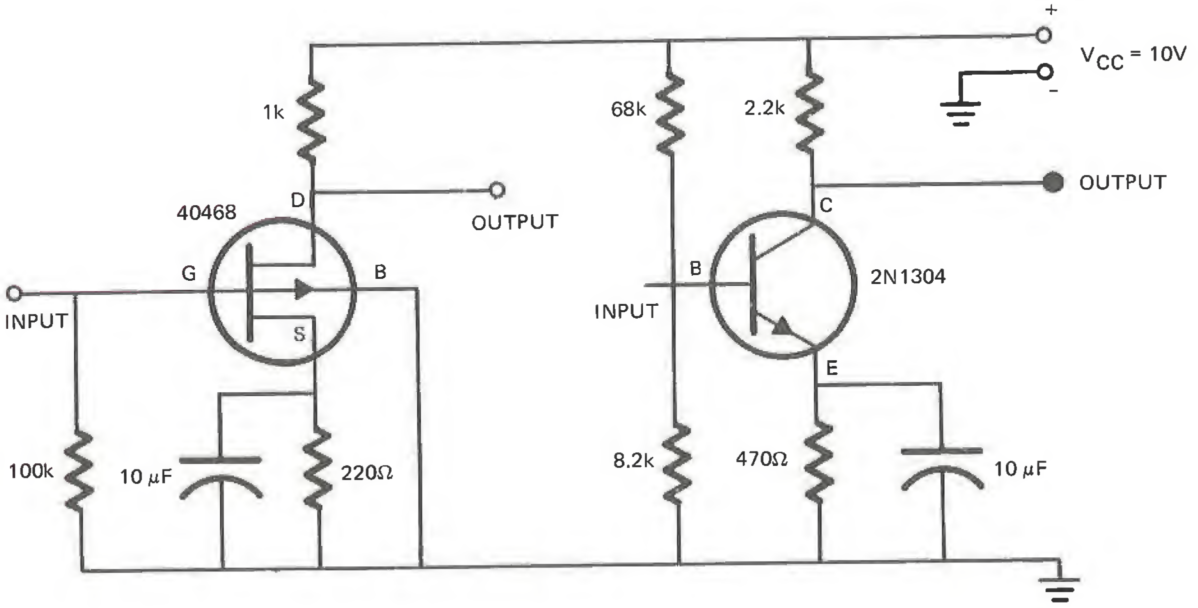


Fig. 18-5 The Experimental Amplifiers

2. Assemble both amplifier circuits at opposite ends of the same breadboard.
3. Measure the quantities computed in step 1 and record the results in the data table.
4. Using the capacitor substitution box, couple the two amplifiers together as indicated in figure 18-6. Set the box for its maximum capacitance value.
5. Connect the oscilloscope, audio generator, VOM, 2.2k load resistor, 1 megohm resistor, and 10 μF capacitor as shown in figure 18-6.

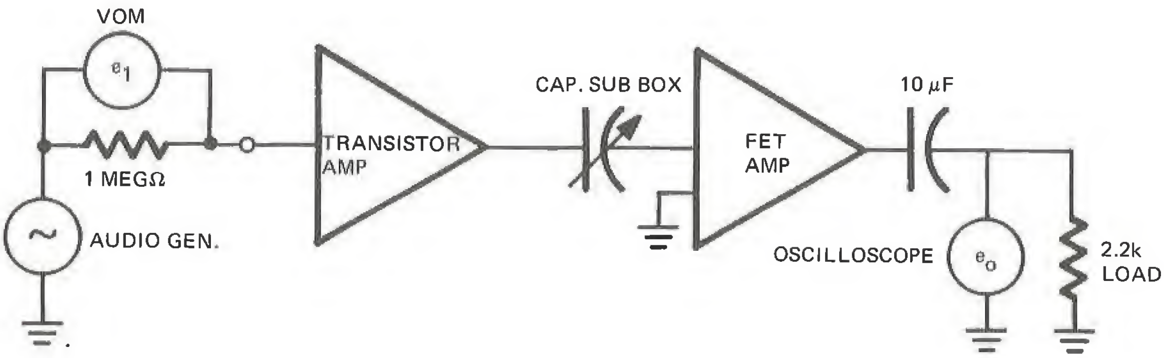


Fig. 18-6 The Experimental Circuit

6. Set the audio generator to a frequency of 1kHz and adjust the level for the maximum undistorted output sinewave.
7. Record the overall current gain of the circuit and the value of the capacitor substitution box.
8. Reduce the capacitor substitution box one step and repeat step 7.
9. Continue reducing the capacitance, repeating step 7 for each value available in the substitution box.
10. Interchange the positions of the transistor amplifier stage and the FET stage and repeat steps 4 through 9.

Quiescent Conditions

QTY	FET Circuit		Transistor Circuit	
	V_{DS}	V_{GS}	V_{CE}	V_{BE}
Computed Value				
Measured Value				

First Test Circuit

Capacitor																				
K_i																				

Second Test Circuit

Capacitor																				
K_i																				

Fig. 18-7 The Data Tables

11. On a single sheet of graph paper plot curves of the current gain versus the values of X_C for the data runs.

ANALYSIS GUIDE. In the analysis of these data you should discuss the trend revealed by your results. Explain why the gain went down as X_C went up and why the two sets of results were different.

PROBLEMS

1. A certain amplifier has an output resistance of 8KΩ and is to be used to drive an 8Ω load. A transformer having 3000 primary turns is available. The transformer secondary is found to be tapped at 100, 300, 1000, and 1500 turns (see figure 18-8). How would you connect the transformer for the best impedance match?

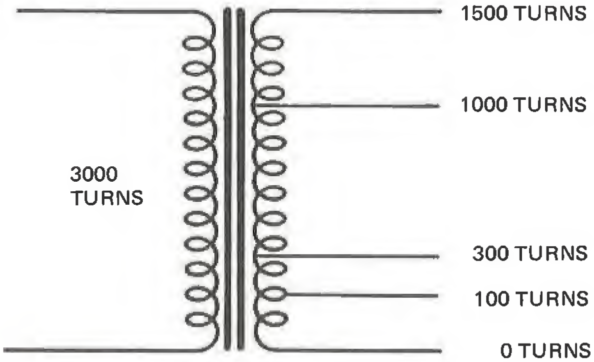


Fig. 18-8 Transformer for Problem 1

2. Explain why RC and direct coupling would probably not be satisfactory in the situation described in problem one.

experiment 19 MULTISTAGE AMPLIFIER GAIN

INTRODUCTION. In many cases the gain of a multistage amplifier is such a large number that it becomes troublesome to handle. It is common practice in such a case to express the gain in a logarithmic unit called *a decibel.* In this experiment we shall examine the ways in which these units are applied in amplifier gain analysis.

DISCUSSION. An electronic circuit having some signal power (P_i) applied to its input and subsequently reproducing it at a different output level (P_o) is said to have a power gain of

$$\boxed{K_P = \frac{P_o}{P_i}} \qquad (19.1)$$

It is often convenient to express this gain in terms of decibels as

$$\boxed{G = 10 \log K_P \text{(decibels)}} \qquad (19.2)$$

One of the advantages of expressing gain in decibels is that successive gains are simply additive. For example, consider the three stages shown in figure 19-1, where the gains are given as ratios.

If we apply 1.0 mW to the input, then the power at P_1 will be 100 mW. At P_2 we will have 10W and at P_o the power will be 1 kW. The overall power gain K_{PT} is one million

$$K_{PT} = \frac{1 \text{kW}}{1 \text{ mW}} = 10^6$$

which is, of course, the same as the product of the three individual gains.

$$\boxed{K_{PT} = K_{P1} K_{P2} K_{P3}} \qquad (19.3)$$

Expressed in decibels this becomes

$$G_T = 10 \log K_{PT}$$

or

$$G_T = 10 \log K_{P1} K_{P2} K_{P3}$$

which we may rewrite as

$$G_T = 10 \log K_{P1} + 10 \log K_{P2} + 10 \log K_{P3}$$

and finally

$$\boxed{G_T = G_{P1} + G_{P2} + G_{P3}} \qquad (19.4)$$

In other words, we may simply add the individual stage gains to get the total gain if they are all expressed in decibels. In the above example, the individual gains are

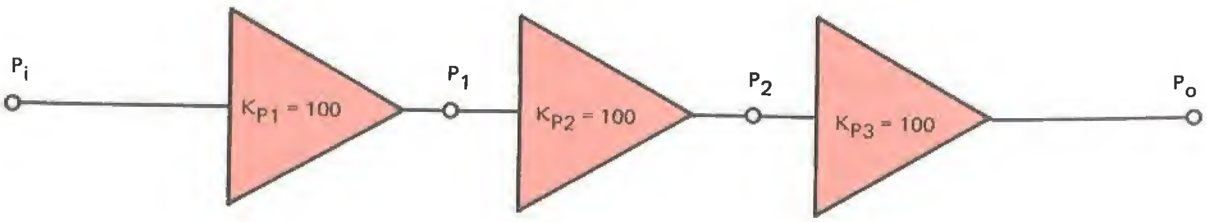


Fig. 19-1 A 3-Stage Amplifier

$$G = 10 \log 100 = 20 \text{ db}$$

and the total gain will be

$$G_T = 20 + 20 + 20 = 60 \text{ db}$$

which is, of course, equivalent to the previous result ($K_{PT} = 10^6$).

Since the input and output powers may be expressed as

$$P_i = \frac{e_i^2}{R_i} \text{ and } P_o = \frac{e_o^2}{R_L}$$

we may rewrite equation 19.2 in the form

$$G = 10 \log \frac{e_o^2/R_L}{e_i^2/R_i}$$

And *if* R_i and R_L are equal, we may write

$$G = 10 \log \left(\frac{e_o}{e_i}\right)^2$$

which may be arranged in the form

$$G = 20 \log \frac{e_o}{e_i} \text{ (decibels)} \qquad \textbf{(19.5)}$$

In many practical cases, **R_i is not equal to R_L.** Equation 19.5 is nevertheless, commonly used to express the voltage gain in decibels.

$$\boxed{A_v = 20 \log K_v \text{(db)}} \qquad \textbf{(19.6)}$$

Voltage gains in decibels are handled in the same ways as power gains in db. For instance, if the voltage gains of the stages in figure 19-1 were

$$K_{v1} = 10\ K_{v2} = 50, \text{ and } K_{v3} = 20$$

these gains could be expressed in decibels as

$$A_{v1} = 20 \log 10 = 20 \text{ db}$$

$$A_{v2} = 20 \log 50 = 34 \text{ db}$$

$$A_{v3} = 20 \log 20 = 26 \text{ db}$$

And the total voltage gain in db would be

$$A_{vT} = 20 + 34 + 26 = 80 \text{ db}$$

The input and output powers can also be expressed as

$$P_i = i_i^2 R_i \text{ and } P_o = i_o^2 R_L$$

Therefore, equation 19.2 can be written as

$$G = 10 \log \frac{i_o^2 R_L}{i_i^2 R_i}$$

And when R_i and R_L are equal, we have

$$G = 10 \log \left(\frac{i_o}{i_i}\right)^2$$

which may be rewritten as

$$G = 20 \log \frac{i_o}{i_i} \text{ (decibels)} \qquad \textbf{(19.7)}$$

Even when R_i is not equal to R_L, we use this relationship to express current gain in decibels as

$$A_i = 20 \log K_i \text{ (db)} \qquad \textbf{(19.8)}$$

And, as in the case of power and voltage gain,

the total gain of several stages may be found by addition.

If the current gains in figure 19-1 are $K_{i1} = 10$, $K_{i2} = 2$, and $K_{i3} = 5$, we may express them in decibels as

$$A_{i1} = 20 \log 10 = 20 \text{ db}$$

$$A_{i2} = 20 \log 2 = 6 \text{ db}$$

$$A_{i3} = 20 \log 5 = 14 \text{ db}$$

And the total current gain would be

$$A_{iT} = 20 + 6 + 14 = 40 \text{ db}$$

In some cases (particularly with passive circuits), the input level may be greater than the output level. In such a case the gain will be less than one. To illustrate this, consider the circuit shown in figure 19-2.

The voltage, current, and power gains of this network are

$$K_v = 5/10 = 0.5$$

$$K_i = 10/500 = 0.02$$

$$K_P = \frac{50 \times 10^{-3}}{5} = 0.01$$

Expressing the gains in decibels we have

$$A_v = 20 \log 0.5 = -20 \log \frac{1}{0.5}$$
$$= -20 \log 2 = -6 \text{ db}$$

$$A_i = 20 \log 0.02 = -20 \log \frac{1}{0.02}$$
$$= -20 \log 50 = -34 \text{ db}$$

$$G = 10 \log 0.01 = 10 \log \frac{1}{0.01}$$
$$= -10 \log 100 = -20 \text{ db}$$

Notice that the decibel gains are negative numbers and may be considered *losses.*

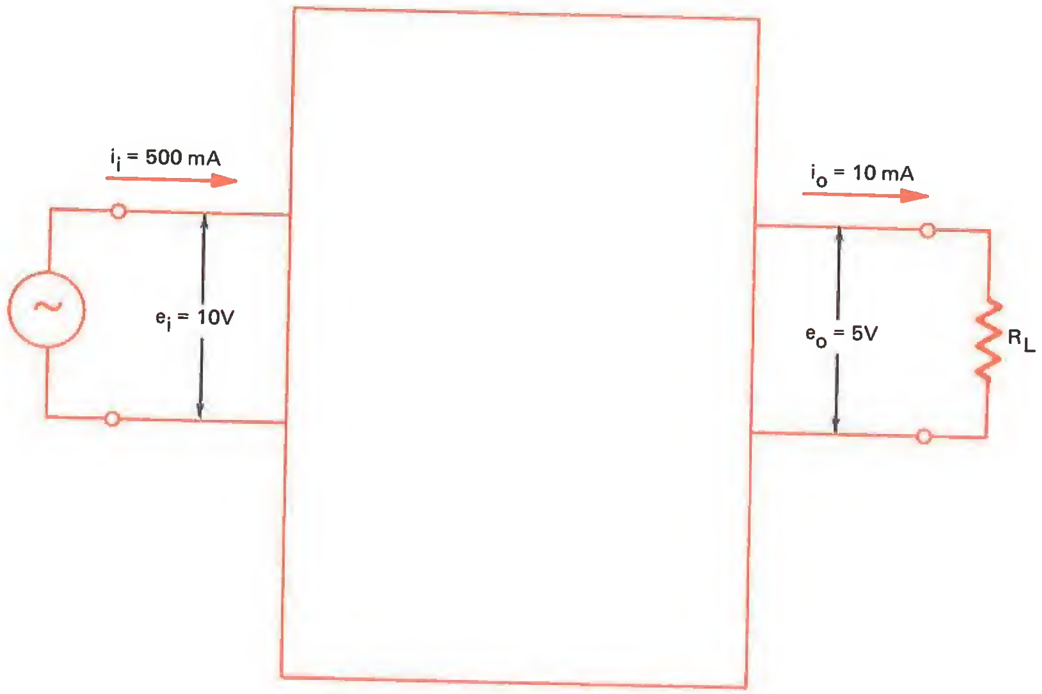


Fig. 19-2 A Passive Network

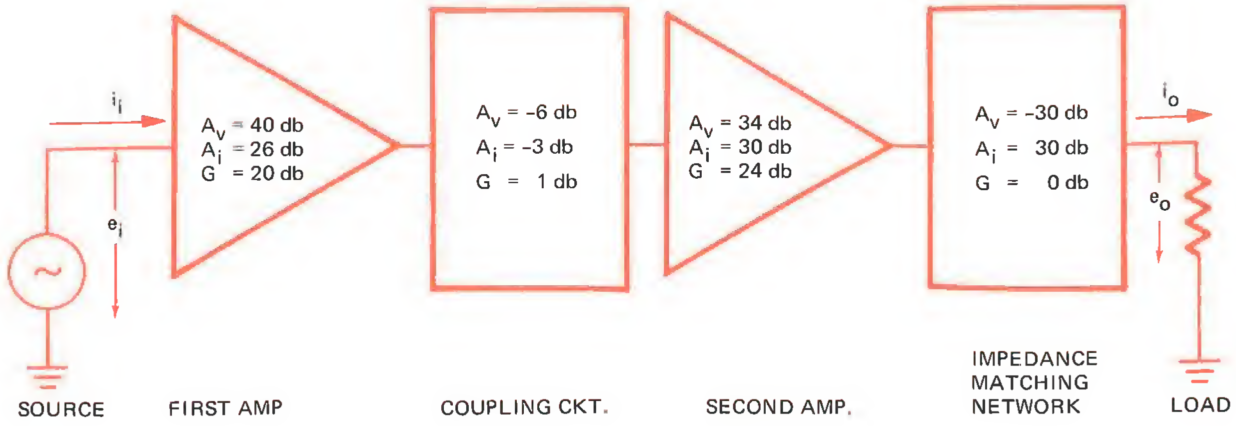


Fig. 19-3 A Typical Multistage Amplifier

Most practical multistage amplifiers have both positive gains and negative gains present in the circuit. Figure 19-3 shows a typical arrangement. In this case the total gains are

$$A_{vT} = 40 - 6 + 34 - 30 = 38 \text{ db}$$

$$A_{iT} = 26 - 3 + 30 + 30 = 83 \text{ db}$$

$$G_T = 20 - 1 + 24 + 0 = 43 \text{ db}$$

Decibels are used very frequently in discussing amplifier performance and are, therefore, important to the technician.

MATERIALS

- 2 NPN transistors (2N1304 or equivalent)
- 1 100k resistor 1/2W
- 1 47k resistor 1/2W
- 2 6.8k resistor 1/2W
- 2 4.7k resistor 1/2W
- 1 3.3k resistor 1/2W
- 2 560 ohm resistors 1/2W
- 1 100 ohm resistor 1/2W
- 1 Variable DC power supply (0–40V)
- 1 Oscilloscope
- 1 Audio generator
- 1 Resistance substitution box (15–10 megohms 1/2W)
- 2 10 μF capacitors (25W VDC)
- 2 100 μF capacitors (25W VDC)

PROCEDURE

1. Assemble the circuit shown in figure 19-4 neatly on a breadboard. Set the resistance substitution box for about 22k ohms.
2. Assemble the audio generator and voltage divider circuit shown in figure 19-5.
3. Set the generator frequency to 1 kHz and the output level to zero.
4. Connect the source to the input of the amplifier. Also connect the oscilloscope across the 4.7k load resistor.

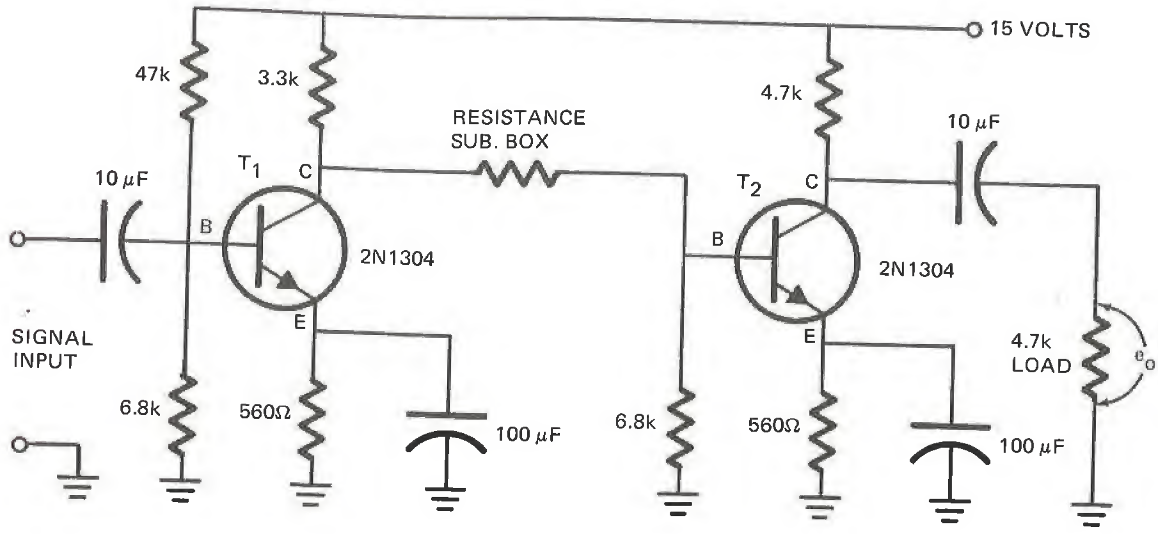


Fig. 19-4 The Experimental Circuit

5. Increase the source level until you have the maximum undistorted signal across the 4.7k load.

6. Adjust the resistance substitution box for the maximum undistorted signal across the 4.7k load.

7. Repeat steps 6 and 7 alternately until the maximum possible undistorted signal level is achieved.

8. Record the peak-to-peak output voltage achieved in step 7 (e_o).

9. Move the oscilloscope to the input of T_2 and record the signal voltage (e_2) between base and ground.

10. Record the voltage gain (K_{v3}) of the output stage. Then compute the gain in db and record it as A_{v3}.

11. Move the oscilloscope to the output of T_1 and record the signal voltage (e_1) from collector to ground.

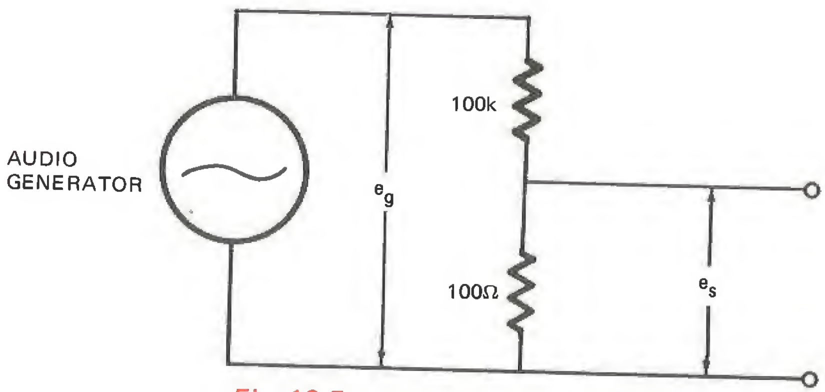


Fig. 19-5 The Experimental Source

12. Compute and record the voltage gains (both K_{v2} and A_{v2}) of the coupling network.
13. Move the oscilloscope to the audio generator terminals and measure e_g. Record the value. Compute e_s using e_g and the voltage divider values. Record e_s in the data table.
14. Compute and record the voltage gains (K_{v1} and A_{v1}) of the input stage.
15. Compute and record the overall voltage gains (K_{vT} and A_{vT}) using the values of e_s and e_o.
16. Determine the overall voltage gain by taking the sum of A_{v1}, A_{v2} and A_{v3}. Record the values as A'_{vT}. Compute and record K'_{vT}.
17. Using A'_{vT}, compute and record K'_{vT}.

Output Stage Data			
e_o	e_2	K_{v3}	A_{v3}

Input Stage Data				
e_g	e_s	e_1	K_{v1}	A_{v1}

Coupling Circuit Data			
e_1	e_2	K_{v2}	A_{v2}

Overall Gain Values			
K_{vT}	A_{vT}	A'_{vT}	K'_{vT}

Fig. 19-6 The Data Tables

ANALYSIS GUIDE. The objective of this experiment has been to become familiar with gain relationships in a multistage amplifier. To that end you should consider the extent to which the two methods of expressing gain are consistent.

PROBLEMS

1. If the value of K_v for a certain amplifier is doubled, how much does A_v increase?
2. Would the results be the same in problem 1 for K and G?
3. If A_v is decreased by 20 db, by what factor must K_v change?
4. Adding a stage to an amplifier increases G by 10 db. How much did the ratio of P_o/P_i increase?

INTRODUCTION. All amplifier circuits include some reactive quantities. Because these quantities change reactance with frequency, the gain of an amplifier also varies with frequency. In this experiment we shall examine the way in which gain varies at low, medium, and high frequencies.

DISCUSSION. For a given single-stage amplifier, there is nearly always a range of frequencies within which the reactive effects of the circuit components may be ignored. This range of frequencies is called the *mid-band* range. In this mid-band range the gain of the amplifier is *not* affected by the reactive components and we may compute the gain value using the familiar small-signal equations. The value of the mid-band gain is usually represented by the symbol A_m.

If we allow the input signal frequency (f) to decrease, the reactances of all of the capacitive elements in the circuit will increase according to

$$X_C = \frac{1}{2\pi f C}$$

In most practical cases, the signal coupling capacitors will have the most pronounced effect on the gain at low frequencies.

If we consider only the input coupling network, then we can draw the low frequency equivalent circuit of an amplifier as shown in figure 20-1. In the mid-band range, the reactance of the coupling capacitor will be much less than the amplifier input resistance. Consequently, the gain of the coupling network (C_c and R_{in}) will be approximately zero decibels (that is, $e_{in} \approx e_s$). The overall gain will, therefore, equal A_m.

As the signal frequency is lowered, X_C increases until at some point (f_1) it equals R_{in}. At this point we have

$$X_C = R_{in}$$

or

$$\frac{1}{2\pi f_1 C_c} = R_{in}$$

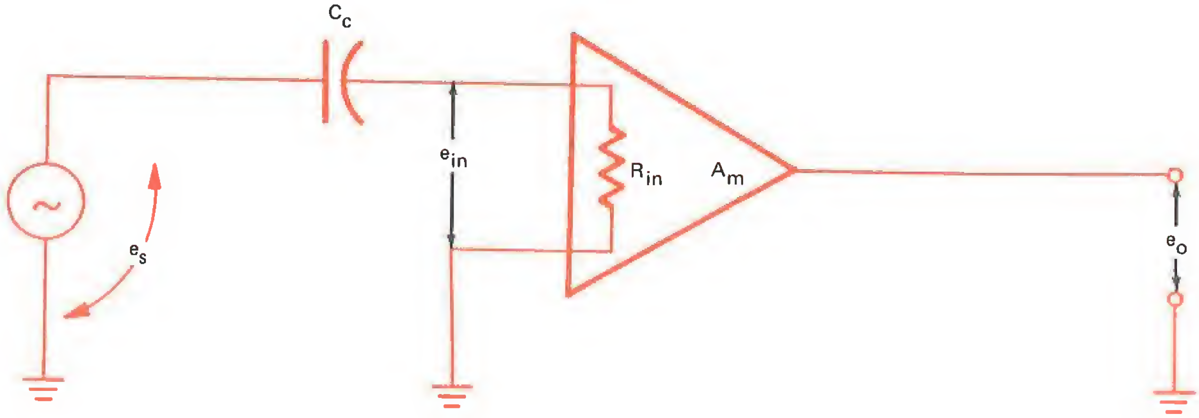


Fig. 20-1 An Amplifier Low Frequency Equivalent Circuit

Solving this equation for f_1, we see that it is equal to

$$f_1 = \frac{1}{2\pi R_{in} C_c} \tag{20.1}$$

This frequency is normally considered to be the lower limit of the mid-band range. Below this frequency the coupling network has an important effect on the overall gain.

We can determine the overall gain by observing that R_{in} and C_c form a voltage divider and that e_{in} will be

$$e_{in} = e_s \frac{R_{in}}{R_{in} - jX_C} \tag{20.2}$$

At f_1 this equation becomes

$$e_{in} = e_s \frac{R_{in}}{R_{in} - jR_{in}} = e_s \frac{R_{in}}{R_{in}\,(1 - j1)} = e_s\left(\frac{1}{1 - j1}\right)$$

$$e_{in} = e_s \frac{1}{1.414\angle{-45^\circ}} = 0.707\, e_s \angle 45^\circ$$

And the gain of the coupling circuit is

$$\frac{e_{in}}{e_s} = 0.707 = -3 \text{ db at } f_1$$

The overall gain at f_1 is, therefore, either

$$\left.\begin{array}{l} A = 0.707\, A_m \angle 45^\circ \\ \text{or} \\ A = (A_m - 3) \text{ decibels} \end{array}\right\} \text{at } f_1$$

depending on whether A_m is expressed as e_o/e_{in} or in decibels, respectively.

At frequencies below f_1, the overall gain continues to decrease according to

$$A_{1o} = A_m\left(\frac{1}{1 - j\,(f_1/f)}\right) \tag{20.3}$$

Somewhat the same thing occurs if the signal frequency is increased. At high frequencies, the coupling capacitors may be ignored. However, if we increase the frequency enough, then the shunt capacity of the amplifier becomes significant. At these relatively high frequencies, we can use the equivalent circuit shown in figure 20-2. Notice that C_t is the total equivalent shunt capacity of the amplifier device, circuit, and load. It has been lumped together for simplicity.

As the signal frequency increases, a point

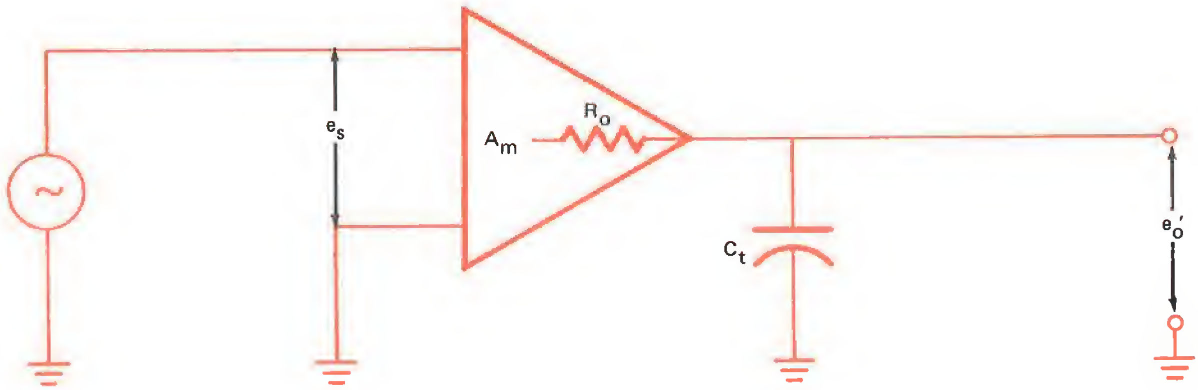


Fig. 20-2 An Amplifier High Frequency Equivalent Circuit

(f_2) will eventually be reached where X_{Ct} will equal R_o. At this frequency we will have

$$X_{Ct} = R_o$$

or

$$\frac{1}{2\pi f_2 C_t} = R_o$$

Therefore, f_2 must have a value of

$$f_2 = \frac{1}{2\pi R_o C_t} \qquad (20.4)$$

At f_2 the voltage divider formed by C_t and R_o will produce an output voltage of

$$e_o' = e_o \frac{-jX_{C_t}}{R_o - jX_{C_t}} = 0.707\, e_o \angle{-45°}$$

and the overall gain will be

$$\left.\begin{array}{l} A = 0.707\, A_m \angle{-45°} \\ \text{or} \\ A = (A_m - 3) \text{ decibels} \end{array}\right\} \text{at } f_2$$

Beyond f_2 the gain will continue to decrease according to

$$A_{hi} = A_m \frac{1}{1 + j\,(f/f_2)} \qquad (20.5)$$

If we now combine the low, mid, and high frequency effects, we have an equivalent circuit like the one shown in figure 20-3. The frequency response of such an amplifier will fall off at both the low and high frequency end. If we plot gain versus frequency, the result would be as shown in figure 20-4.

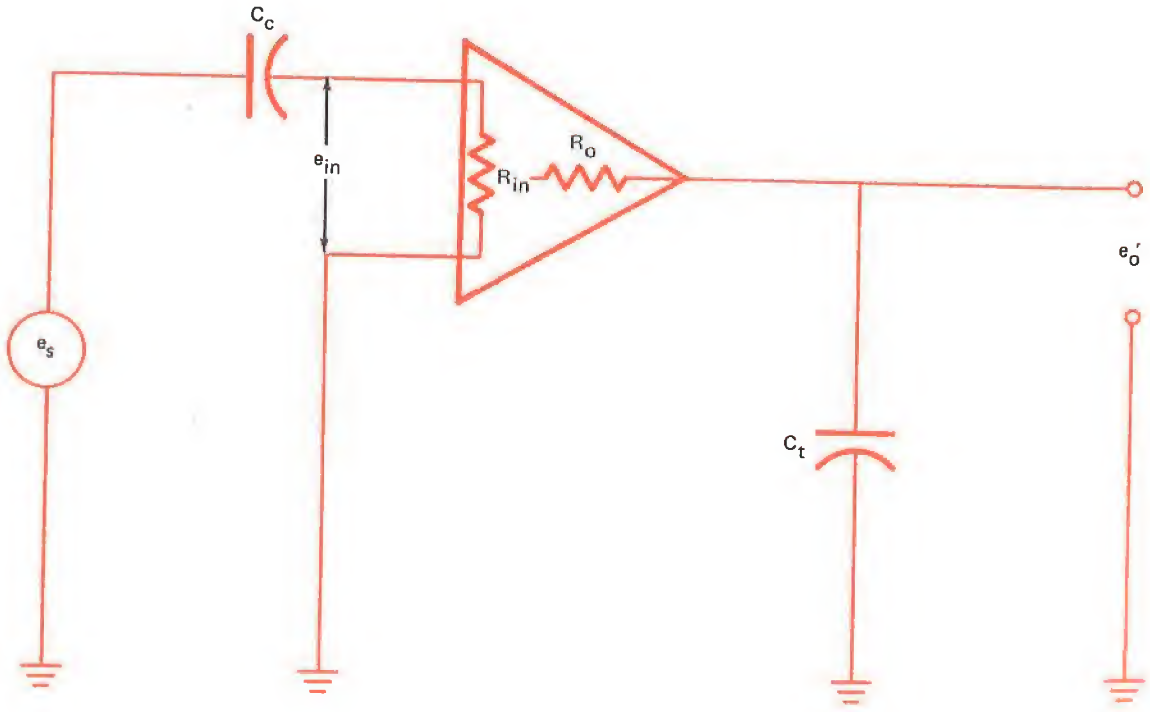


Fig. 20-3 A Broad Band Amplifier Equivalent Circuit

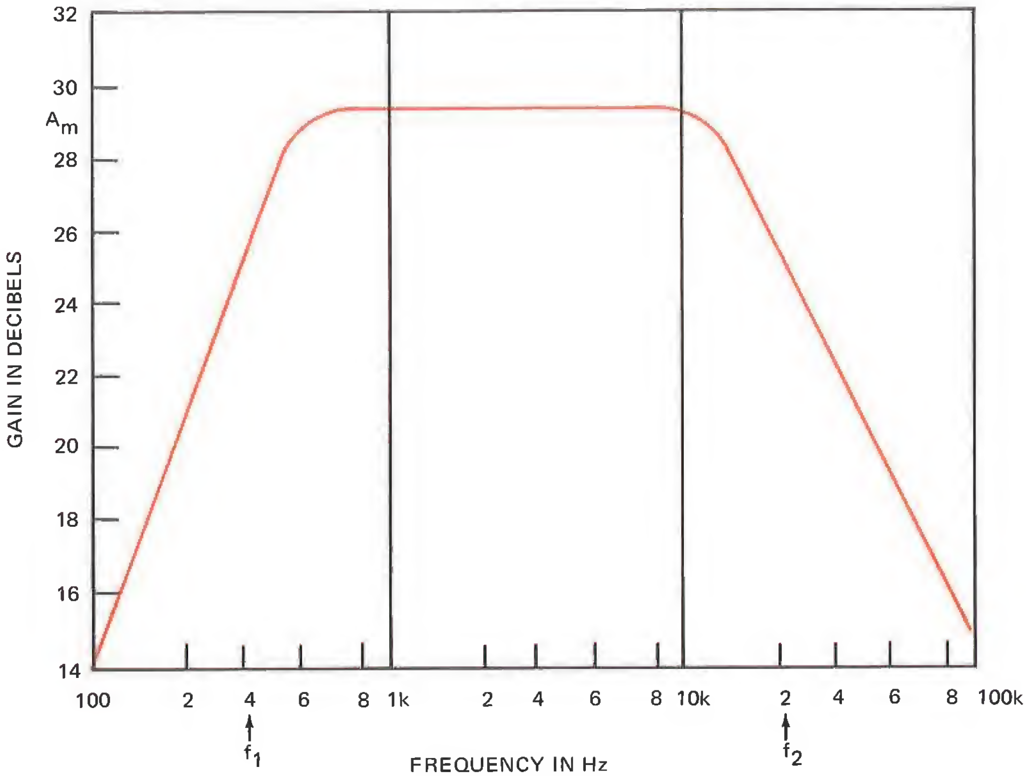


Fig. 20-4 A Typical Amplifier Frequency Response

It is worth noticing that the gain is usually plotted in decibels while frequency is in Hertz. Semilog graph paper is normally used for plotting frequency response curves.

The *bandwidth* of the amplifier is usually considered to be the mid-band range between the −3 db points on the frequency response curve. In other words, the bandwidth of the amplifier extends from f_1 to f_2:

$$BW = f_2 - f_1 \text{(Hz)} \qquad \textbf{(20.6)}$$

Frequency response data is usually taken by holding the input signal level constant while varying the signal frequency and measuring the output level.

MATERIALS

1 Integrated operational amplifier (type SN724 or equivalent)
1 Variable DC supply (0–30 volts)
1 IC socket for the amplifier
1 VOM or FEM
1 Audio generator
1 Oscilloscope
1 0.01 μF capacitor 600W VDC
1 0.1 μF capacitor 600W VDC
1 220k resistor 1/2W
1 47Ω resistor 1/2W
1 Breadboard
1 Sheet, 3 cycle semilog graph paper (K&E 46 5490 or equivalent
1 Resistance substitution box (15–10 megohm 1/2W)
2 1k resistors 2W

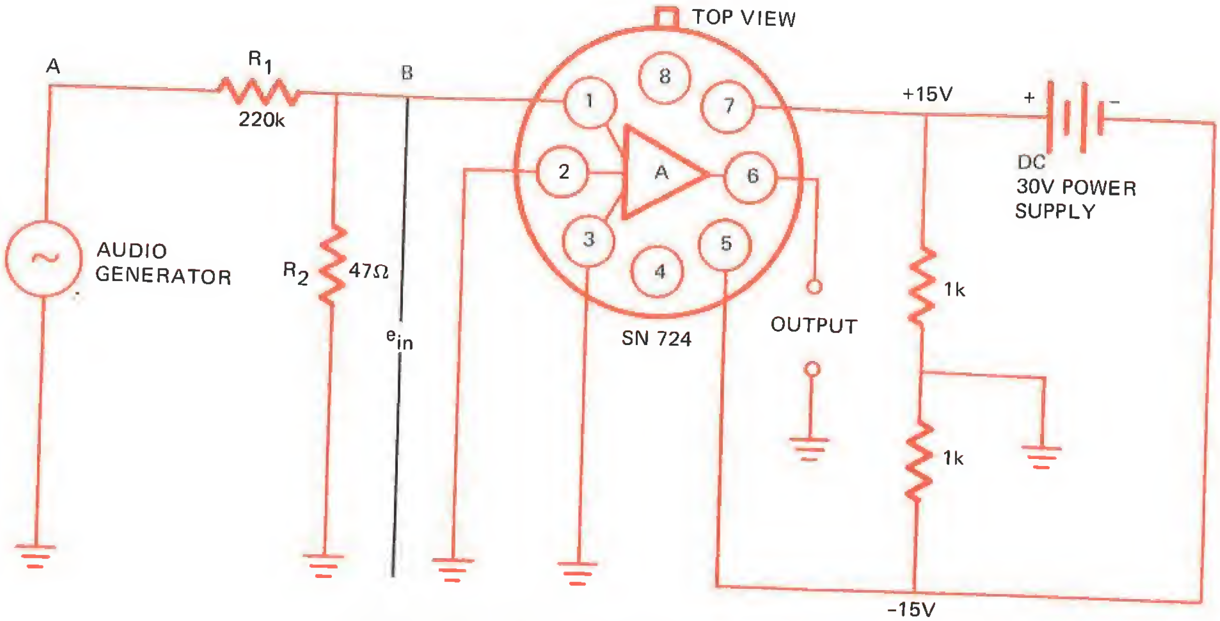


Fig. 20-5 The Experimental Circuit

PROCEDURE

1. Assemble the circuit shown in figure 20-5. **Be sure that both power supply terminals are isolated from ground.**
2. Connect the oscilloscope across the amplifier output terminals.
3. Adjust the signal generator for the maximum undistorted output at 1 kHz. Record the input voltage (e_{in}).
4. With the input voltage held constant, measure and record the output voltage at frequencies of:

100 Hz	1 kHz	10 kHz
200 Hz	2 kHz	20 kHz
300 Hz	3 kHz	30 kHz
400 Hz	4 kHz	40 kHz
500 Hz	5 kHz	50 kHz
600 Hz	6 kHz	60 kHz
700 Hz	7 kHz	70 kHz
800 Hz	8 kHz	80 kHz
900 Hz	9 kHz	90 kHz

5. Compute and record the gain in decibels for each frequency in step 4.
6. On semilog paper, plot the frequency response of the amplifier.
7. Using the 220k resistance and C_c = 0.01 μF, compute and record f_1.

	No Cap.		Series Cap.		Both Cap.	
f (Hz)	e_o (volts)	A_v (db)	e_o (volts)	A_v (db)	e_o (volts)	A_v (db)
100						
200						
300						
400						
500						
600						
700						
800						
900						
1k						
2k						
3k						
4k						
5k						
6k						
7k						
8k						
9k						
10k						
20k						
30k						
40k						
50k						
60k						
70k						
80k						
90k						

e_{in}	
f_1 Comp.	
f_1 Curve	
f_2 Comp.	
f_2 Curve	

Fig. 20-6 The Data Tables

8. Insert the 0.01 μF capacitor in series with the input at point A and repeat steps 4 through 6.
9. From your curve, determine the value of f_1.
10. Using the 47Ω resistance (R_2) and $C_s = 0.1\ \mu F$, compute and record f_2.
11. Connect the 0.1 μF capacitor across the input of the amplifier at point B and repeat steps 4 through 6.
12. From your curve, determine f_2.

ANALYSIS GUIDE. In the analysis of these data, there are several points that you should consider. Some of them are: Did the computed and graphical values of f_1 agree? Did your measured frequency response curves agree with figure 20-4 in general shape?

PROBLEMS

1. If the value of f_1 for the first stage of a two-stage amplifier is 50 Hz and f_1 for the second stage is 150 Hz, what would be f_1 for the whole amplifier?
2. If the mid-band gain of the first stage above is 100 (40 db), what would be its gain at 10 Hz?
3. The second stage above has a mid-band gain of 140 (40 db). What would be its gain at 10 Hz?
4. What would be the overall gain above at 10 Hz? At 200 Hz?

experiment 21 DIFFERENTIAL AMPLIFIERS

INTRODUCTION. *Differential amplifier* circuits are used in a great variety of electronic applications. In this experiment we shall consider some of the most important characteristics of these circuits.

DISCUSSION. In many instrumentation and measurement situations, it is necessary to compare two electronic signals and produce an output proportional to their difference. An amplifier which performs this function is called a *difference* or *differential* amplifier.

Let us consider the amplifier shown in figure 21-1. If the amplifier does indeed amplify the difference between e_1 and e_2, then the output voltage will be

$$e_o = A\,(e_1 - e_2)$$

We may rewrite this relationship in the form

$$e_o = Ae_1 = Ae_2$$

which shows that, if the difference amplifier is to operate ideally, then both e_1 and e_2 must experience the same gain (A) from input to output. While this *is* theoretically possible, in most practical cases e_1 and e_2 will undergo slightly different values of amplification. The output of a practical amplifier would therefore be

$$e_o = A_1e_1 - A_2e_2 \qquad (21.1)$$

If e_1 and e_2 are different (non-zero) values, then the overall gain will be the average of A_1 and A_2 and is called the *difference mode gain.*

$$\boxed{A_d = \frac{A_1 + A_2}{2}} \qquad (21.2)$$

On the other hand, if e_1 and e_2 are exactly equal (and non-zero), then the output should be zero since the difference voltage $(e_1 - e_2)$ is zero. In practice this will not be the case because A_1 and A_2 are slightly different. If we define the *common mode input voltage* e_c to be equal to the average of e_1 and e_2

$$e_c = \frac{e_1 + e_2}{2}$$

Then when $e_1 = e_2$ we have $e_c = e_1 = e_2$, and equation 21.1 becomes

$$e_o = A_1e_c - A_2e_c$$

or

$$\frac{e_o}{e_c} = A_1 - A_2$$

This ratio (e_o/e_c) is called the *common mode gain* (A_c) of the amplifier:

$$\boxed{A_c = A_1 - A_2} \qquad (21.3)$$

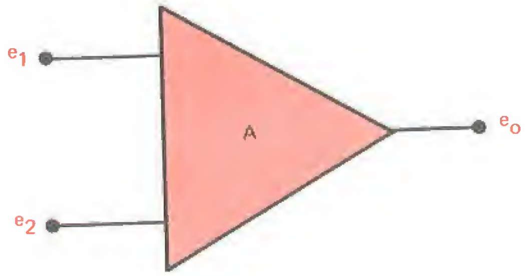


Fig. 21-1 A Differential Amplifier

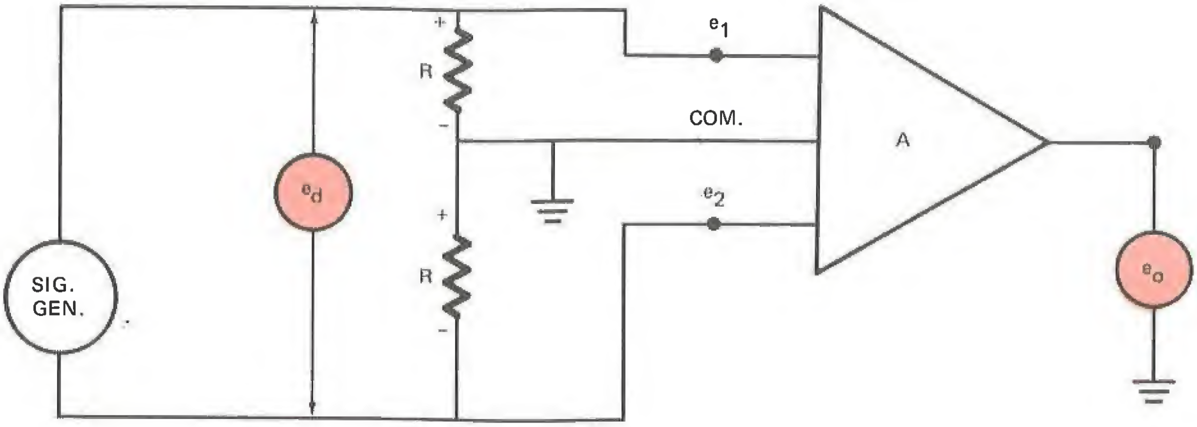


Fig. 21-2 Measuring A_d

The quality of a differential amplifier is usually judged by taking the ratio of the difference mode gain to the common mode gain. This ratio is called the *common mode rejection ratio*

$$\boxed{\rho = \frac{|A_d|}{|A_c|}} \tag{21.4}$$

and is frequently expressed in decibels.

It is worth noting at this point that if we define the difference mode input as

$$e_d = e_1 - e_2 \tag{21.5}$$

and the common mode input as

$$e_c = \frac{e_1 + e_2}{2} \tag{21.6}$$

then we may solve simultaneously for e_1 and e_2 and get

$$e_1 = e_c + 1/2\, e_d \text{ and } e_2 = e_c - 1/2\, e_d$$

Substituting these values into equation 21.1 renders

$$e_o = A_1\,(e_c + 1/2\, e_d) - A_2\,(e_c - 1/2\, e_d)$$

or

$$e_o = A_1 e_c + \frac{A_1\, e_d}{2} - A_2\, e_c + \frac{A_2\, e_d}{2}$$

Then collecting voltage terms, we have

$$e_o = e_c\,(A_1 - A_2) + e_d\,(\frac{A_1 + A_2}{2})$$

However, since $(A_1 - A_2)$ and $(\frac{A_1 + A_2}{2})$ are the common mode and difference mode gains respectively, we have

$$e_o = A_d e_d + A_c e_c \tag{21.7}$$

which is the equation normally used to describe the output voltage of a difference amplifier. Equation 21.7 also provides us with a means of measuring A_d and A_c. Consider the circuit shown in figure 21-2.

If the two resistors in figure 21-2 are equal, then $e_1 = -e_2$ and from equations 21.5 and 21.6

$$e_d = e_1 - e_2 = e_1 - (-e_2) = e_1 + e_2 \text{ volts}$$

and

$$e_c = \frac{e_1 + e_2}{2} = \frac{e_1 + (-e_2)}{2} = \frac{e_1 - e_2}{2} = 0 \text{ volts}$$

Since e_c is zero, we can measure e_o and e_d and compute A_d.

$$A_d = \frac{e_o}{e_d}$$

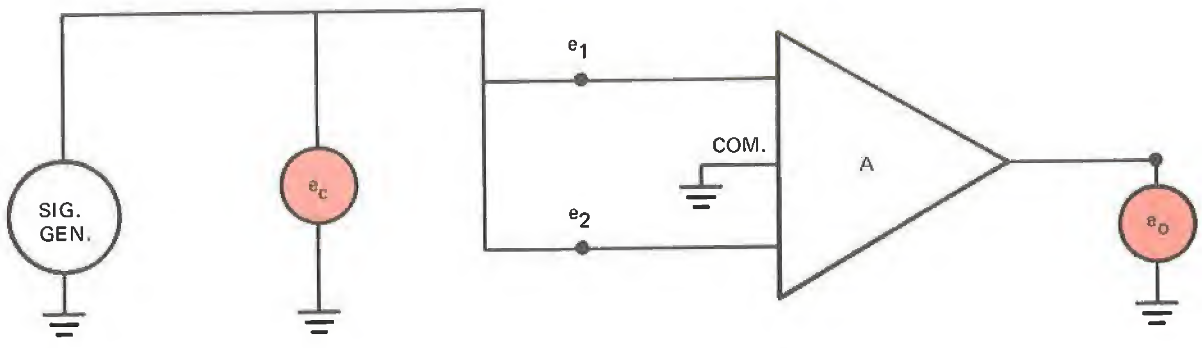


Fig. 21-3 Measuring A_c

Similarly, we can measure A_c with the circuit shown in figure 21-3. In this case $e_1 = e_2$; therefore, $e_d = 0$ and $e_c = 1/2\ (e_1 + e_2)$. Therefore, by measuring e_o and e_c we have A_c.

$$A_c = \frac{e_o}{e_c}$$

With A_d and A_c known, we find the common mode rejection ratio using equation 21.4.

Differential amplifiers may be constructed using any type of active devices and may have either balanced or unbalanced outputs, as shown in figure 21-4.

In some cases, the emitter resistor is replaced with a third active device (transistor or FET). When this is done, it is possible to achieve a common mode gain close to zero.

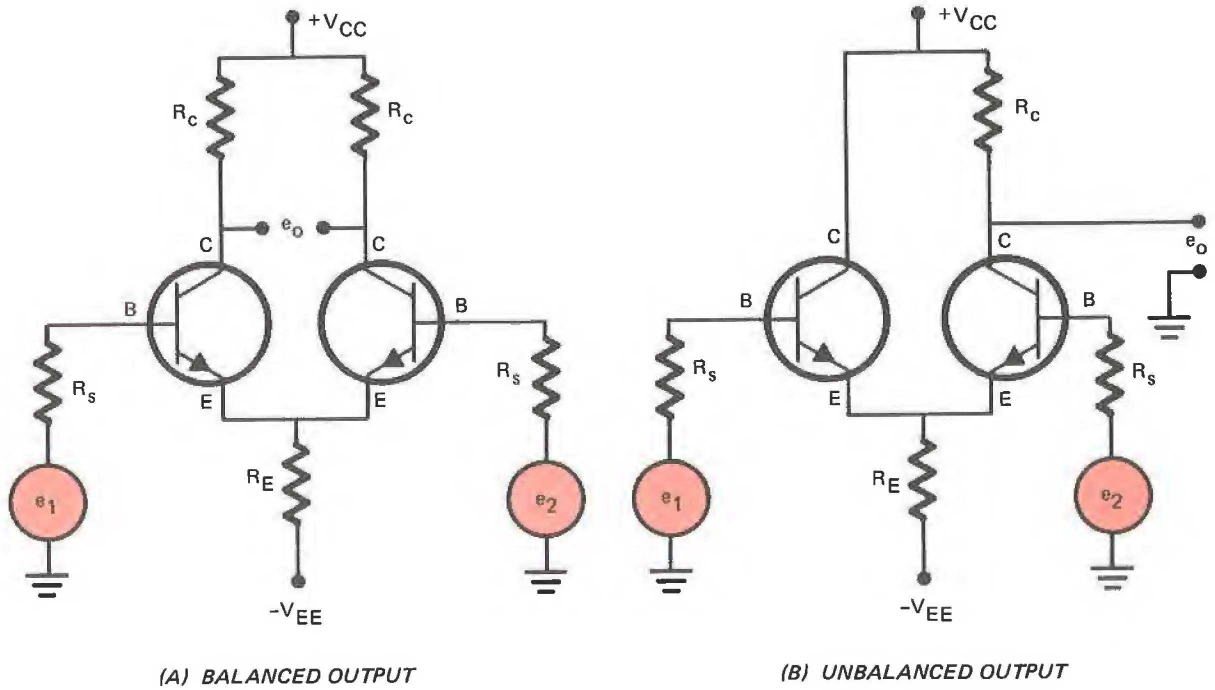


Fig. 21-4 Transistor Differential Amplifiers

MATERIALS

1 Integrated operational amplifier (type SN724 or equivalent)
1 Data sheet for the above IC
1 Variable DC supply (0 – 40V)
1 VOM or FEM
1 Audio generator (with balanced under-ground output)
1 Oscilloscope
1 IC socket
1 Breadboard
2 10k resistors 1/2W
2 220 ohm resistors 2W
1 1k resistor 2W

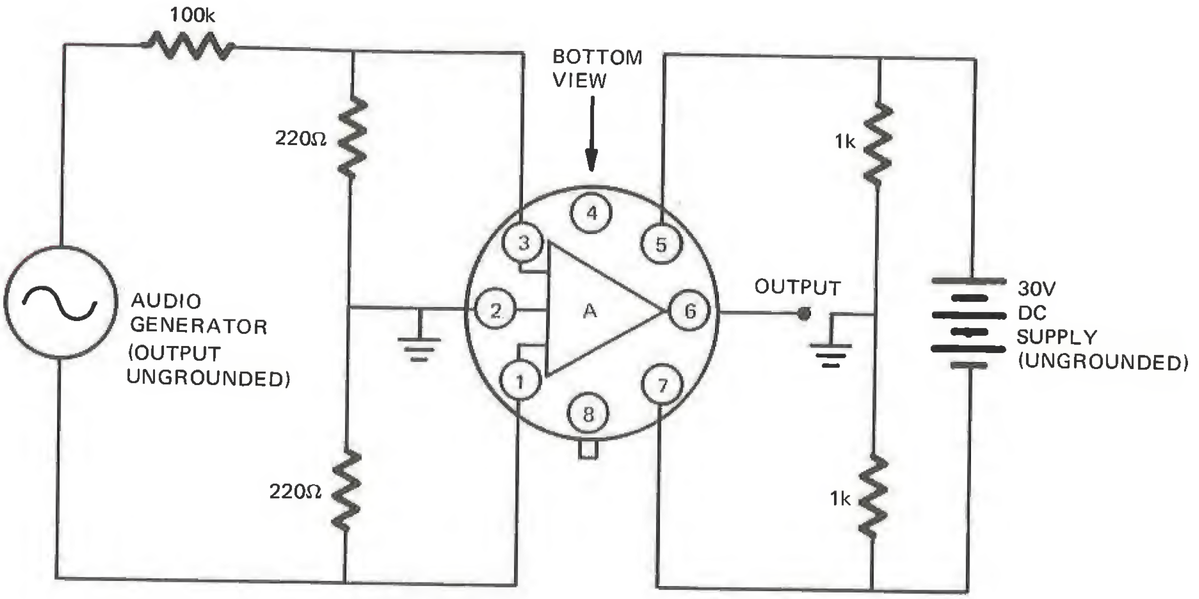


Fig. 21-5 The First Experimental Circuit

PROCEDURE

1. Assemble the operational amplifier circuit shown in figure 21.5.
2. Connect the oscilloscope to the amplifier output.
3. Set the audio generator for an undistorted amplifier output at 1 kHz.
4. Record the value of the output signal, e_o.
5. Move the oscilloscope to the input and measure e_1 and e_2.
6. Compute and record e_d and e_c. Be sure to use the correct signal polarities in making these calculations.
7. Compute and record either A_d or A_c as the case may be.
8. Compute the common mode rejection ratio of the amplifier, ρ.

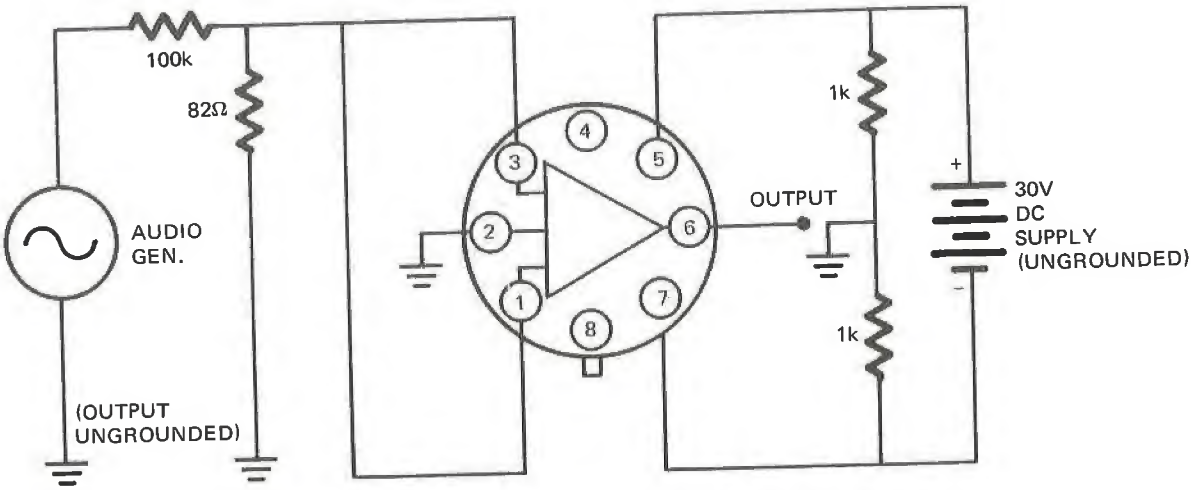


Fig. 21-6 The Second Experimental Circuit

9. Make the changes in the input connections required to produce the circuit shown in figure 21-6.
10. Repeat steps 2 through 7 using this circuit.
11. Compute the common mode rejection ratio of the amplifier, ρ.

ANALYSIS GUIDE. In the analysis of these data, you should compare your measured values of A_d and ρ to those given in the manufacturer's data sheet. Also consider possible reasons for any difference between the values.

PROBLEMS

1. A certain differential amplifier has an output of 50 volts when e_1 = 0.5V and e_2 = -0.5V. When e_1 = 1V and e_2 = 1V, the output is 0.05 volts. What is the value of A_d, A_c, and ρ?
2. What would be the output voltage in problem 1 if e_1 = 1V and e_2 = 0?
3. Draw a circuit diagram of an FET differential amplifier with a balanced output.

Qty	e_o	e_1	e_2	e_d	e_c	A_c	A_d	ρ
First Ckt								
Second Ckt								

Fig. 21-7 The Data Table

experiment 22 *FEEDBACK PRINCIPLES*

INTRODUCTION. In electronic amplifiers it is common practice to mix a portion of the output signal with the input signal to produce a change in the circuit performance. In this experiment we shall examine a typical type of *feedback* and its effects on amplifier performance.

DISCUSSION. To produce electronic feedback, a sample of the output voltage or the output current is fed back to the input circuit. Since voltage feedback is perhaps more common, we shall limit this discussion to it.

Let us examine the circuit shown in figure 21-1 which represents a generalized case of voltage feedback. In this circuit we see that the gain of the amplifier alone is given by

$$A = \frac{e_o}{e_{in}} \qquad (22.1)$$

and that the output voltage is sampled by the feedback network (β). A portion of the output voltage ($\beta\, e_o$) is connected in series with the input circuit such that the input voltage is the sum of the signal voltage and the feedback voltage,

$$e_{in} = e_s + \beta\, e_o$$

Substituting this value into equation 21.1 gives us

$$A = \frac{e_o}{e_s + \beta\, e_o}$$

or

$$A\, e_s + A\beta\, e_o = e_o$$

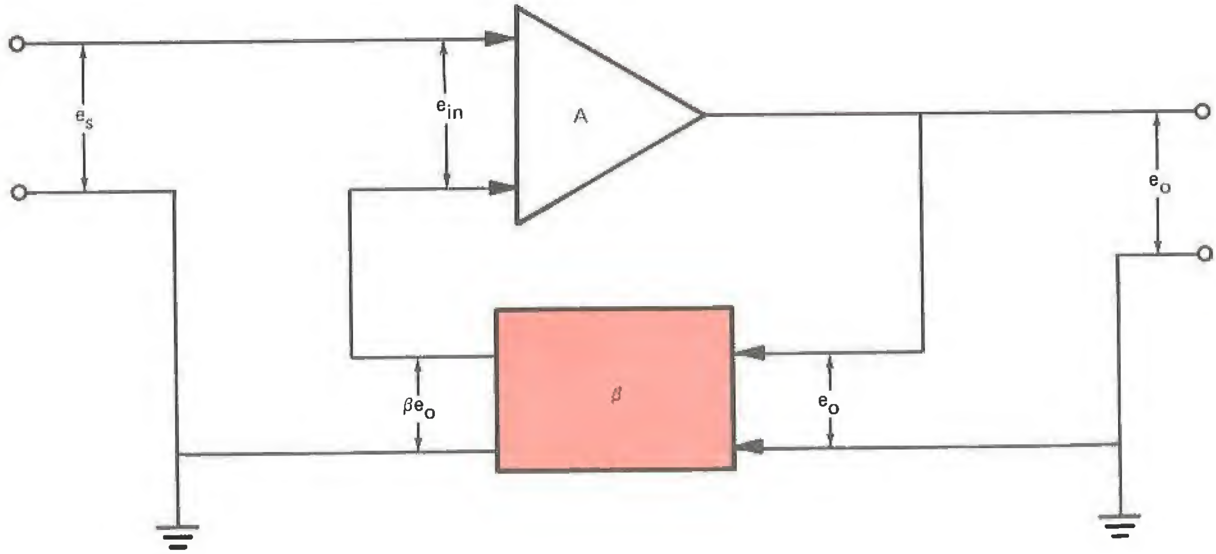


Fig. 22-1 Voltage Feedback

Collecting the e_o on the right provides

$$Ae_s = e_o - A\beta\, e_o$$

and

$$Ae_s = e_o\,(1 - A\beta)$$

which may be rewritten in the form

$$\frac{e_o}{e_s} = \frac{A}{1 - A\beta}$$

Returning to the original circuit we observe that the ratio of e_o/e_s is, in fact, the overall gain with feedback. If we call this overall gain A', then we have

$$\boxed{A' = \frac{A}{1 - A\beta}} \qquad (22.2)$$

This equation is a very important one as it raises two possible feedback situations. When the product of $A\beta$ is positive (A and β have the same sign, ie., both positive or both negative) then A' can be greater than A. This condition is called *regenerative* or *positive* feedback and occurs when the fed back voltage (βe_o) is in phase with the input signal. This type of feedback is employed extensively in oscillator circuits but is only rarely used with amplifier circuits.

On the otherhand, when $A\beta$ is negative (A and β have opposite signs, ie., one positive and the other negative) A' will be less than A and the situation is termed *degenerative* or *negative* feedback. This is by far the more common case in amplifier circuits. To achieve degeneration, the output sample (βe_o) is fed back 180 degrees out of phase with the input signal. In most cases this is achieved by having a negative gain ($-A$) and a positive β ($+\beta$).

There are several advantages to be had by employing negative feedback. For example, let's consider what happens to the overall gain (A') if the *open loop* gain (A) changes. The overall gain is

$$A' = \frac{A}{1 - A\beta}$$

Differentiating A' with respect to A we have

$$\frac{dA'}{dA} = \frac{1}{1 - A\beta}\,\frac{A'}{A} = \frac{A'}{A\,(1 - A\beta)}$$

and

$$dA' = \frac{A'}{A\,(1 - A\beta)}\,dA \qquad (22.3)$$

To illustrate the effect of this equation, suppose that $\beta = 0.1$, and $A = -1000$. From equation 22.2 we have

$$A' = \frac{A}{1 - A\beta} = \frac{-1000}{101} = -9.9$$

Now if A suddenly (or otherwise) changes to -900 then dA would be -100 and dA' is

$$dA' = \frac{A'}{A\,(1 - A\beta)}\,dA = \frac{-9.9}{81{,}900} \times 100 = -0.0121$$

Therefore, when A changed by 10%, A' changed by only about 0.1%. That is, when A changes from -1000 to -900, A' changes from -9.9 to -9.8. As a result we say that the feedback has *stabilized* the gain against variation.

Another advantage of degenerative feedback is in the area of distortion reduction. Consider an amplifier which produces the desired output voltage and adds some distortion voltage (D) of its own. A fraction of the net distortion voltage ($\beta D'$) is fed back 180° out of phase with the input signal and appears at the output amplified by an amount equal to the open loop gain. The net output distortion (D') then is the sum of the original

distortion plus the amplified fraction that is fed back

$$D' = D + A\beta D'$$

and

$$\boxed{D' = \frac{D}{1 - A\beta}} \qquad \textbf{(22.4)}$$

Using the previous example, if the open loop distortion was 10 percent of the output voltage, then the distortion with feedback would be

$$D' = \frac{0.1}{101} \approx 0.001$$

or approximately .1 percent of the output.

The bandwidth of an amplifier is also affected by feedback. Under normal circumstances the high and low frequency gains of an amplifier are equal to

$$A_{hi} = \frac{A_m}{1 + j\,f/f_2} \text{ and } A_{lo} = \frac{A_m}{1 - j\,f_1/f}$$

where A_m is the mid-band gain, f_1 and f_2 are the lower and upper three db points, respectively, while f is the operating frequency.

If we substitute these two relationships into equation 22.2, they reduce to

$$A'_{hi} = \frac{A_m}{1 - A_m\beta + j\,f/f_2} \text{ and}$$

and

$$A'_{lo} = \frac{A_m}{1 - A_m\beta - j\,f_1/f}$$

and the upper and lower three db points become

$$f'_2 = f_2\,(1 - A_m\beta) \text{ and } f'_1 = f_1/(1 - A_m\beta) \qquad \textbf{(22.5)}$$

Feedback also tends to alter the input and output resistances of an amplifier. In the case of the input resistance, the voltage fed back is out of phase with the input signal and therefore opposes the flow of input current. As a result the input resistance increases with feedback by an amount

$$\boxed{R'_i = R_i\,(1 - A\beta)} \qquad \textbf{(22.6)}$$

In the case of the output resistance, the gain stabilizing effect of feedback tends to reduce it. It is very difficult to arrive at a general expression which will predict the change in output resistance caused by feedback. However, in many cases

$$\boxed{R'_o \approx \frac{R_o}{1 - A\beta}} \qquad \textbf{(22.7)}$$

is a useful approximation.

MATERIALS

1 Integrated operational amplifier SN724 or equivalent
1 IC socket
1 Breadboard
1 Variable DC power supply (0 - 40V)
1 Oscilloscope
1 Resistance substitution box (15 - 10 megohm 1/2W)
1 Audio generator
1 0.1 μF capacitor 600W VDC
1 100k resistor 1/2W
1 100Ω resistor 1/2W
3 1k resistors 1/2W
1 7.5k resistor 2W
1 VOM or FEM

PROCEDURE

1. Assemble the amplifier circuit shown in figure 22-2.

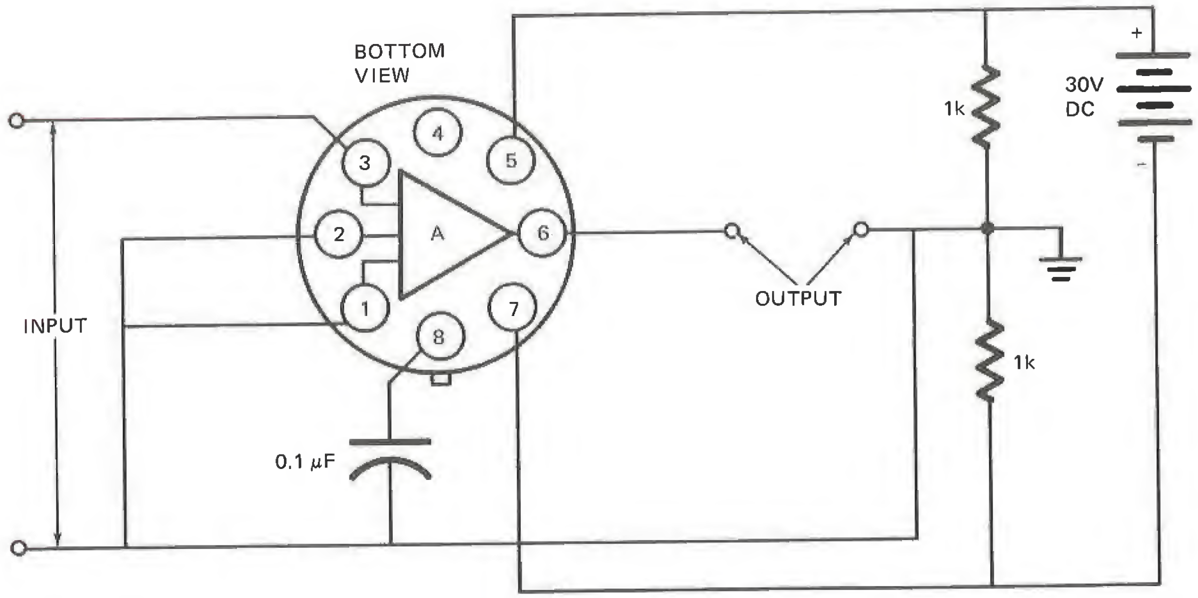


Fig. 22-2 The First Experimental Circuit

2. Assemble the audio generator and source voltage divider as shown in figure 22-3.

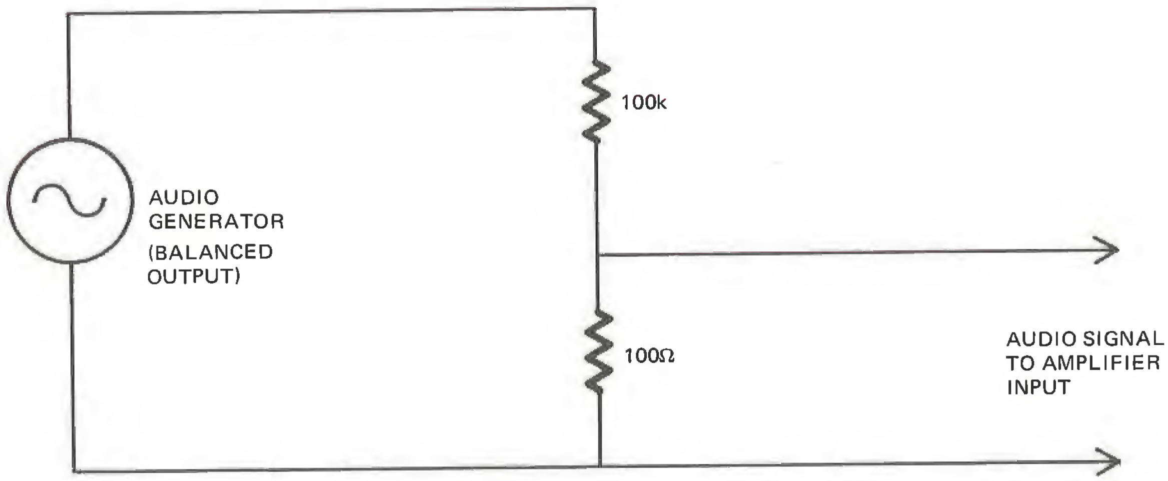


Fig. 22-3 The Audio Source

3. Connect the oscilloscope to the amplifier output and the audio source to the amplifier input.

4. Adjust the audio generator for the maximum undistorted amplifier output at 1kHz. Record the output voltage (e_o).

5. Measure and record the amplifier input voltage (e_s). Compute and record the open loop gain (A_m).

6. Increase the input frequency until the output voltage is 0.707 times that measured in step 4. Record the frequency as f_2.

7. Increase the input signal level until the output waveform is quite visibly distorted. Record the peak-to-peak output (e_x) and make a sketch of the waveform. Reset the input level to that established in step 4.

8. Using the resistance substitution box experimentally, determine and record the values of R_i and R_o.

9. Make the necessary changes in the amplifier circuit to produce the circuit shown in figure 22-4.

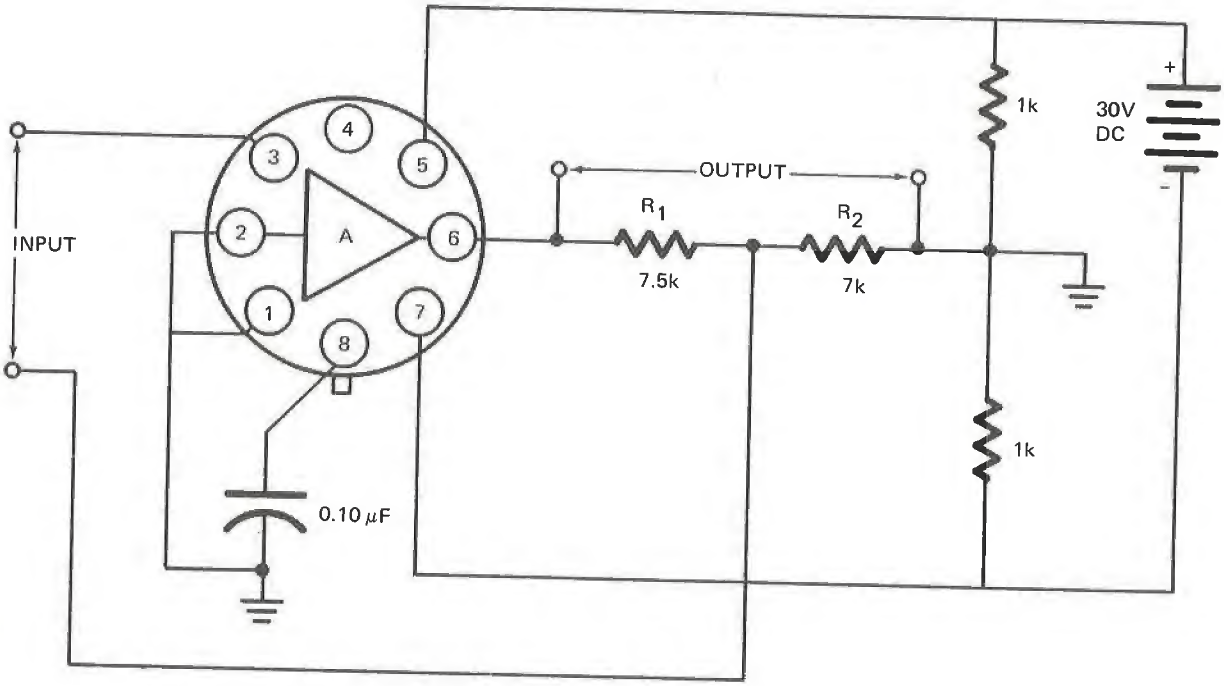


Fig. 22-4 The Second Experimental Circuit

10. Remove the source voltage divider from the audio generator and repeat step 3.

11. Adjust the audio generator for the same output as in step 4. Record the value as e'_o.

12. Repeat steps 5 through 7 recording the results as "feedback values" in the data table.

13. Increase the input signal level until the output is equal to that recorded in step 7. Make a sketch of the waveform.

14. Repeat step 8 and record the results.

15. In this circuit, β is equal to the voltage divider ratio of R_1 and R_2. Compute this value and record it.

16. With the value of β and the open loop parameters measured above, compute and record the values of A'_m, f'_2, R'_i and R'_o using the equations given in the discussion.

QTY	e_s	A_m	f_2	e_x	R_i	R_o	β	e_o
Open Loop Values								
Feedback Values								
Computed Values								

Fig. 22-5 The Data Table

ANALYSIS GUIDE. In the analysis of your results you should consider the effect of feedback on the amplifier parameters and the extent to which the equations given in the discussion accurately predicted the effects.

PROBLEMS

1. A single-stage transistor amplifier has the following parameters:

$h_{fe} = 50$	$h_{ie} = 1500$ ohms	$f_1 = 50$ Hz
$h_{oe} = 40 \times 10^{-6}$ mhos	$h_{re} = 7.5 \times 10^{-4}$	$f_2 = 18$ kHz
$R_L = 5$k ohms	$R_s = 5$k ohms	$D = 5\%$

If a feedback network having a total effective β of +0.05 is used, what would be the values of:

(a) A_v (d) R'_i (g) f'_1

(b) A'_v (e) R_o (h) f'_2

(c) R_i (f) R'_o (i) D'

2. Assume that everything else in problem 1 remained the same when the transistor was replaced with another having an h_{fe} of 100. Which circuit parameters would change?

3. Repeat problem 1 substituting h_{fe} from problem 2.

experiment 23 SINGLE-STAGE FEEDBACK

INTRODUCTION. *Feedback* may be applied around any number of amplifier stages resulting in a variety of possible circuits. When feedback is used within a single-stage amplifier, the resulting circuitry is important enough to justify our special attention. In this experiment we shall examine several commonly used single-stage feedback arrangements.

DISCUSSION. One of the most common ways of applying feedback to a single-stage amplifier is to leave the emitter resistor unbypassed as shown in figure 23-1. The output voltage in this case will be

$$e_o = -i_C R_L \qquad (23.1)$$

and the voltage across the emitter resistor will be

$$e_E = -i_E R_E$$

If we assume that the emitter current is approximately equal to the collector current, then we can say that

$$e_E = i_C R_E \qquad (23.2)$$

Since both the emitter voltage and e_o are directly proportional to i_C, we conclude that e_E is proportional to e_o. In other words,

$$e_E = \beta e_o$$

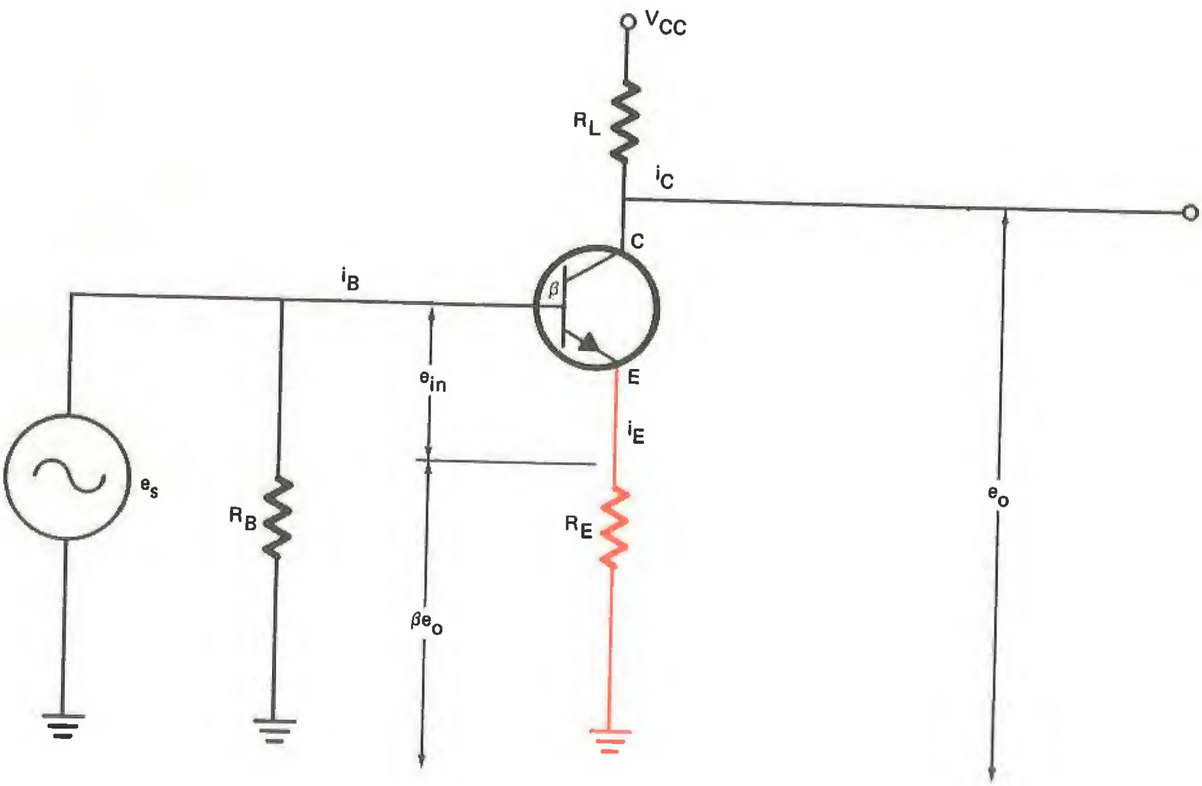


Fig. 23-1 Amplifier With Unbypassed Emitter

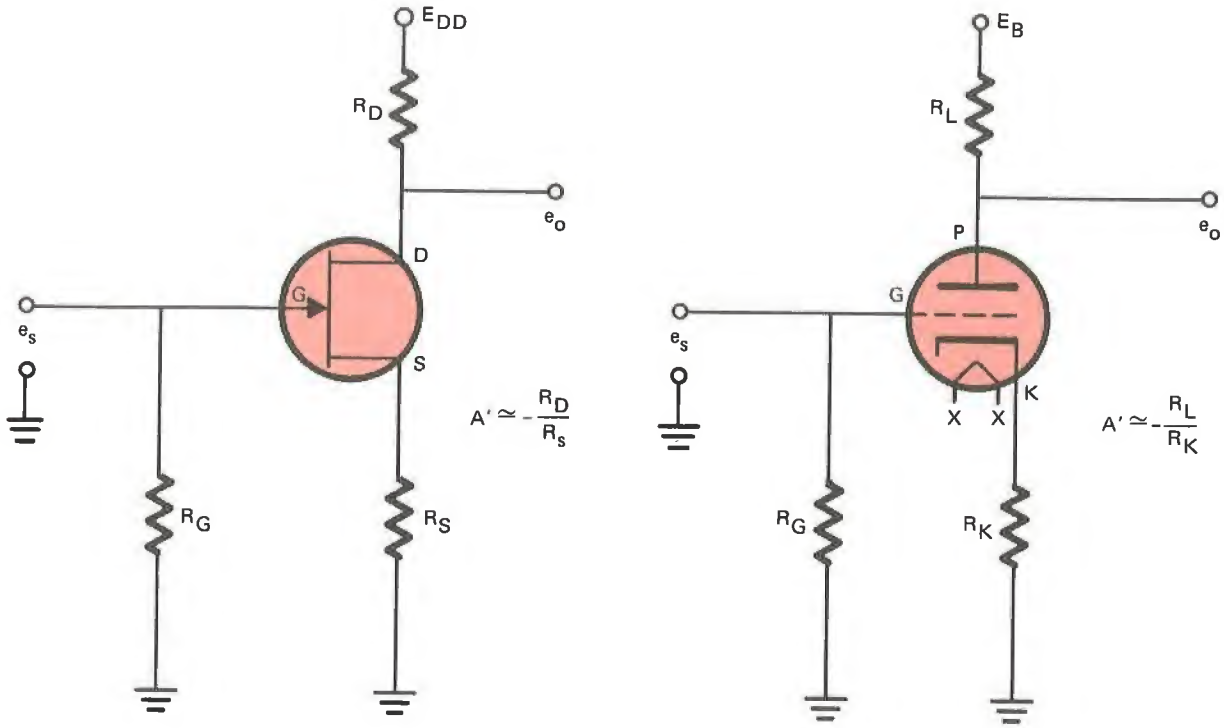


Fig. 23-2 FET and Vacuum Tube Circuits

Substituting equations 23.1 and 23.2 into this expression for e_o and e_E, respectively, we have

$$i_C R_E = \beta i_C R_L$$

or

$$\boxed{\beta = \frac{R_E}{R_L}} \tag{23.3}$$

The gain of the amplifier with R_E unbypassed will be

$$A' = \frac{A}{1 - A\beta}$$

However, if the product $A\beta$ is much greater than 1, then

$$1 - A\beta \approx -A\beta \quad (\text{if } |A\beta| >> 1)$$

and we may simplify the gain to

$$\boxed{A' \simeq \frac{-A}{A\beta} = -\frac{1}{\beta}} \tag{23.4}$$

When this is the case then the gain becomes

$$\boxed{A' \simeq -\frac{R_L}{R_E}} \tag{23.5}$$

It is worth noting at this point that $|A\beta|$ will be much greater than one only if R_L is much greater than R_E.

The amplifier discussed above used a bipolar transistor as an active device. The same circuit can be constructed using an FET or vacuum tube as indicated in figure 23-2. All of these amplifiers exhibit other characteristics of feedback such as reduced distortion, improved gain stability, broader bandwidths, etc.

The idea of using the emitter resistor to provide degeneration can be carried to the extreme by eliminating R_L entirely and taking the output across R_E as shown in figure 23-3. Such a circuit is called an *emitter follower* or *common collector* amplifier.

In such a circuit e_o is given by

$$e_o = i_E R_E$$

and the amount of feedback present is

$$-\beta e_o = i_E R_E$$

Consequently, β becomes

$$\beta = \frac{-i_E R_E}{e_o} = \frac{-e_o}{e_o} = -1 \tag{23.6}$$

and the gain of the stage is

$$\boxed{A' = -\frac{1}{\beta} = 1} \tag{23.7}$$

This special type of feedback amplifier can also be constructed with an FET or tube as shown in figure 23-4. Such amplifiers

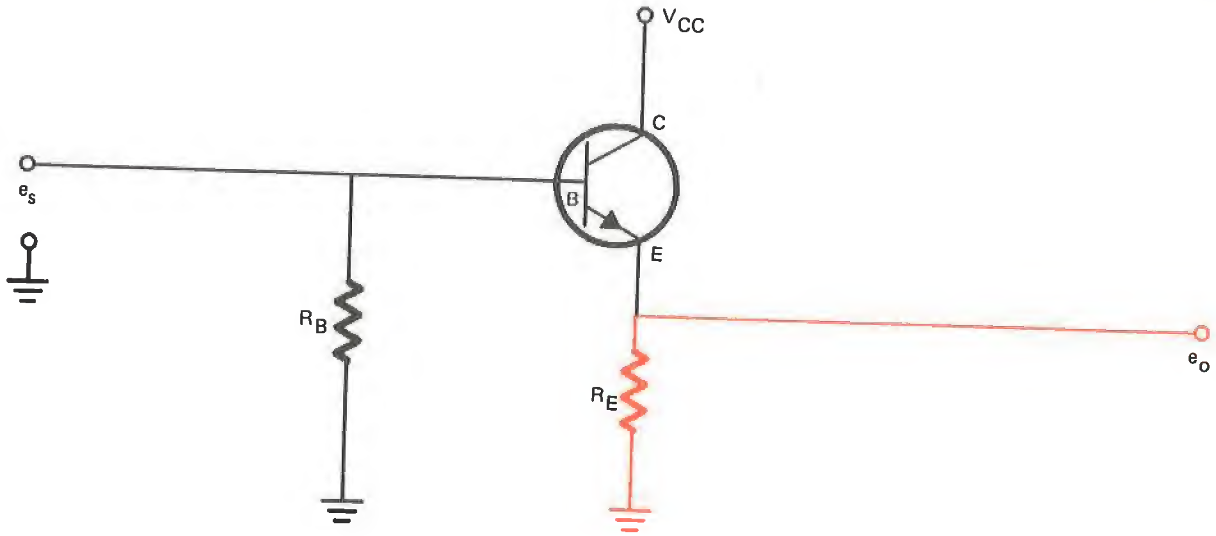


Fig. 23-3 A Common Collector Amplifier

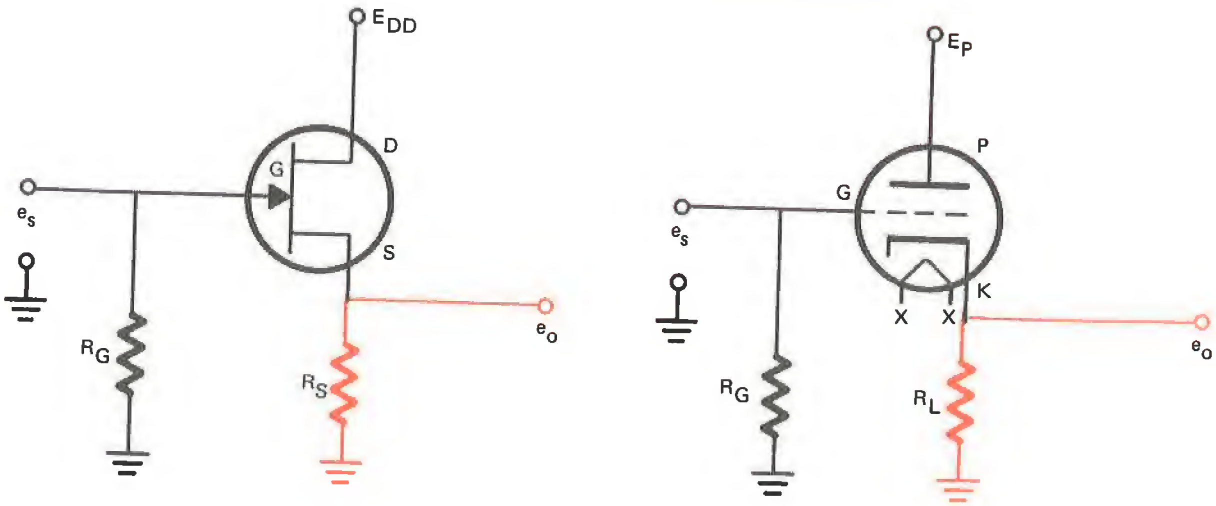


Fig. 23-4 Common Drain and Common Plate Amplifiers

are called *common drain* and *common plate* amplifiers (also source followers and cathode followers). All three are frequently used for electronic impedance matching, having high impedance inputs and low impedance outputs. They also have extremely wide bandwidths (typically several megahertz).

MATERIALS

1 Resistance substitution box (15 – 10 megohm 1/2W)
1 Variable DC power supply (0 – 40V)
1 Audio generator
1 VOM or FEM
1 Oscilloscope
1 Transistor type 2N1304 or equivalent
1 Transistor socket
1 Breadboard
1 100 μF 50W VDC capacitor
2 10 μF 50W VDC capacitors
1 2.2k resistor 1/2W
1 10k resistor 1/2W
1 100k resistor 1/2W
1 100Ω resistor 1/2W
1 47k resistor 1/2W
1 560 ohm resistor 1/2W

PROCEDURE

1. Assemble the circuit shown in figure 23-5.

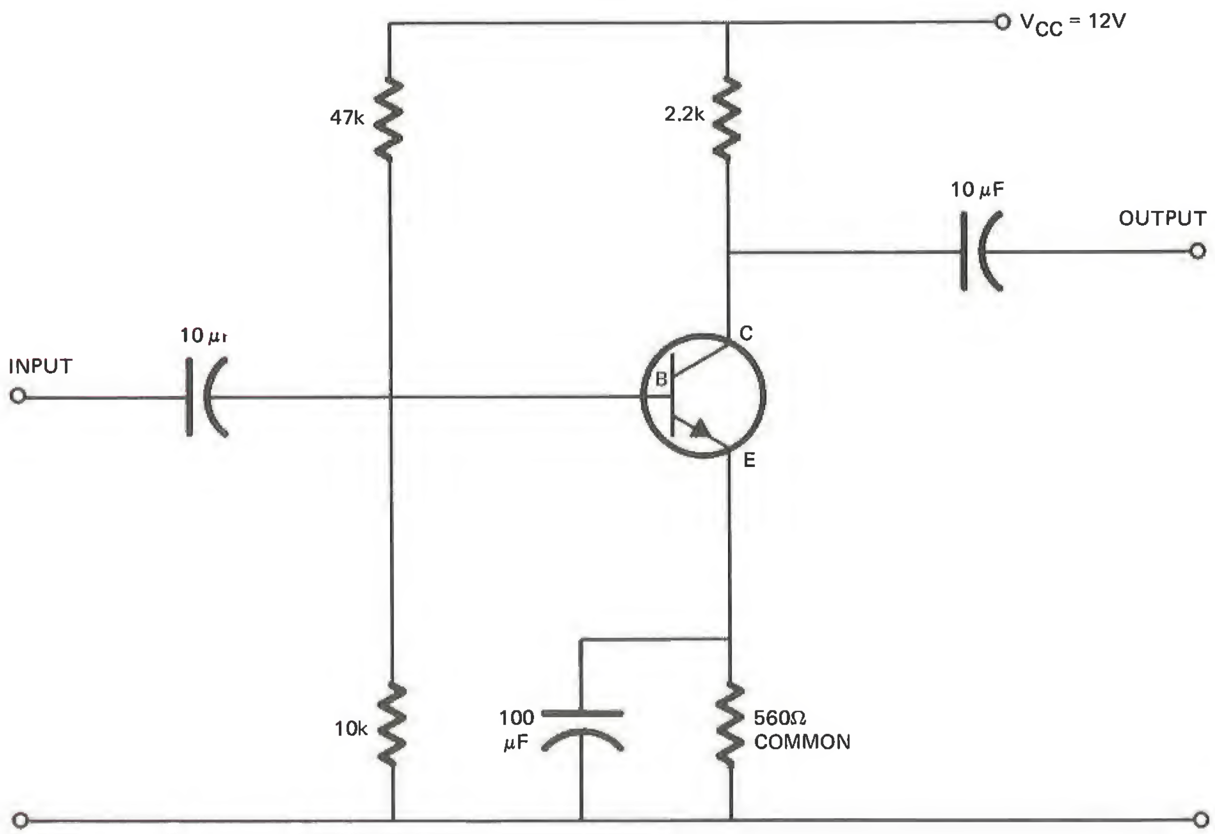


Fig. 23-5 The First Experimental Circuit

2. Measure and record the values of:
   a) The circuit voltage gain, A_v.
   b) The circuit input resistance, R_i.
   c) The circuit output resistance, R_o.
3. Remove the 100 μF emitter bypass capacitor and repeat step 2.
4. Using the circuit values compute and record β.
5. With the appropriate equation from the discussion compute and record A'.
6. Rearrange the circuit as shown in figure 23-6. Use the 2.2k and the 560Ω resistors in series to produce the 2.76k emitter resistor.

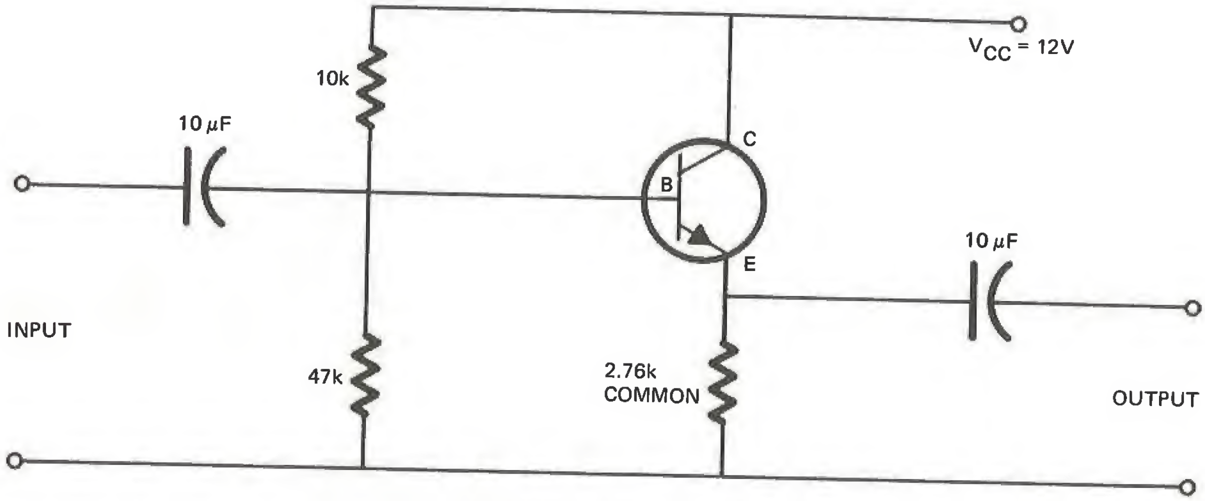


Fig. 23-6 The Second Experimental Circuit

7. Repeat steps 2, 4, and 5.

QTY	A_v Meas.	R_i	R_o	β	A' Comp
Circuit With Emitter Bypassed					
Circuit With Emitter Unbypassed					
Emitter Follower					

Fig. 23-7 The Data Table

ANALYSIS GUIDE. In the analysis of these data you should examine the effect that feedback had on the original amplifiers' parameters. You should also consider the extent to which the equations given in the discussion were effective in predicting circuit performance.

PROBLEMS

1. Explain why the input resistance of a common collector amplifier would normally be larger than that of a common emitter amplifier.
2. What would be the approximate value of the overall gain in figure 23-8? Explain how you arrived at your answer.
3. What is the value of β in each stage of figure 23-8?

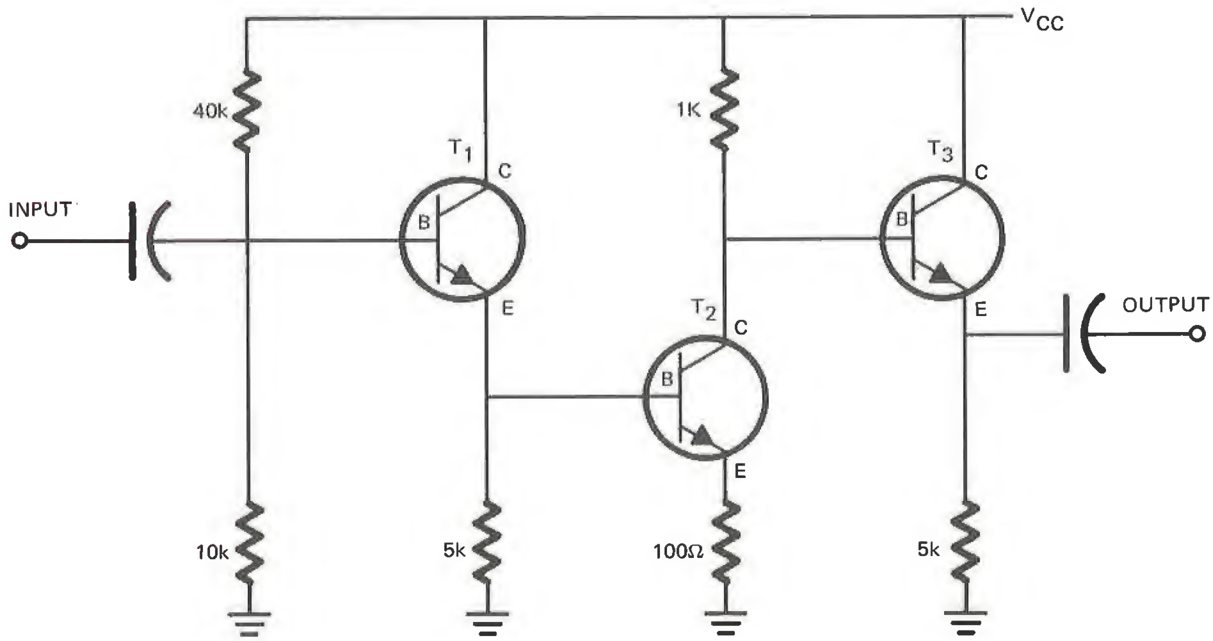


Fig. 23-8 Circuit for Problem 2

experiment 24 SUMMING AMPLIFIERS

INTRODUCTION. One of the important uses of an operational amplifier is to take the algebraic sum of several signals. In this experiment we shall examine the way in which the summing operation is performed.

DISCUSSION. Let us consider the operational amplifier circuit shown in figure 24-1. If the open loop gain of the amplifier is *very* large and the output voltage is only a few volts, then the value of the amplifier input voltage (ϵ) must be *very small*. The currents flowing through R_f and R_i will be

$$i_f = \frac{e_o - e}{R_f} \text{ and } i_s = \frac{e - e_s}{R_i}$$

Now if e is very small compared to either e_o or e_s, we can simplify the current equations to

$$i_f \simeq \frac{e_o}{R_f} \text{ and } i_s \simeq -\frac{e_s}{R_i}$$

Then if i_i is very small compared to either i_f or i_s,

$$i_s \simeq i_f$$

or

$$-\frac{e_s}{R_i} \simeq \frac{e_o}{R_f}$$

which may be rearranged into the form

$$\frac{e_o}{e_s} \simeq -\frac{R_f}{R_i}$$

And we recognize e_o/e_s as the overall gain of the amplifier. That is

$$A' \simeq -\frac{R_f}{R_i}$$

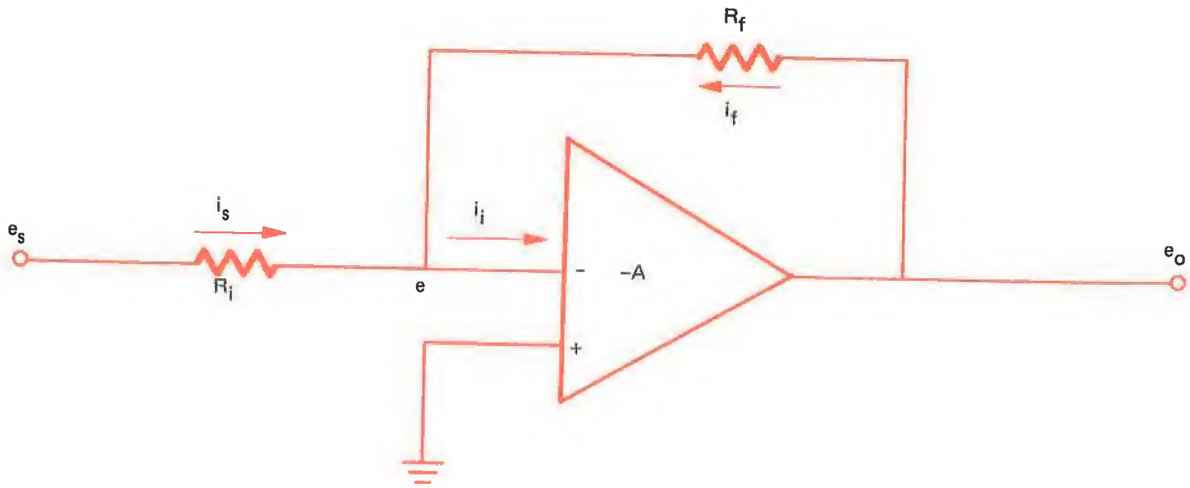


Fig. 24-1 An Operational Amplifier

In practice, operational amplifiers are designed specifically to satisfy the conditions. Their open loop gains high (usually well over 1000) and their input current (i_i) is held to as small a value as possible (frequently 100 μA or less).

Returning to equation 23.1 and presuming the approximation to be a very good one, we may write

$$\boxed{e_o = -\frac{R_f}{R_i} e_s} \tag{24.3}$$

Examination of this equation reveals that we may use the circuit given in figure 24-1 in either of two ways:

1. If $R_f = R_i$, then the circuit serves as an *inverter* or sign changer. That is, it simply changes the sign of e_s.
2. The circuit may also be used to multiply e_s by a constant coefficient equal to $-R_f/R_i$.

In actual practice, the value of R_i is usually restricted to between 1k and 10k ohms; and the ratio of R_f/R_i is normally held to between 0.01 and 100. These restrictions force R_f to lie between 10 ohms and 1 megohm.

To illustrate the use of such amplifiers, let's suppose we have a signal which we wish to multiply by 3.5. To achieve this operation we write

$$e_o = 3.5\ e_s$$

and we set up the circuit shown in figure 24-2.

However, since the output of this circuit is $-3.5\ e_s$, we must add an inverter as shown in figure 24-3. This circuit satisfactorily performs the required multiplication.

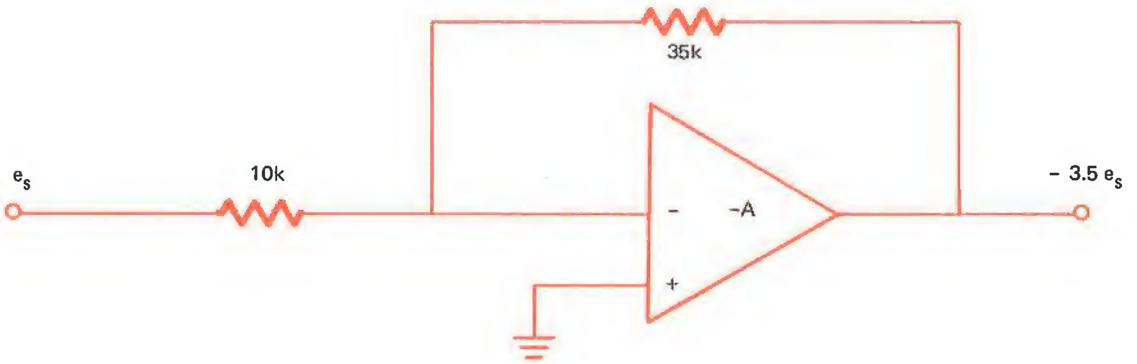


Fig. 24-2 Multiplying e_s by -3.5

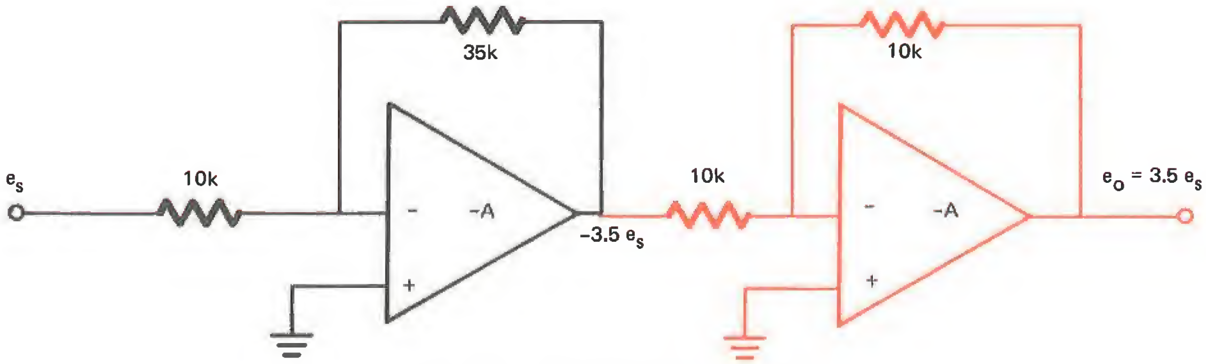


Fig. 24-3 Multiplying e_s by 3.5

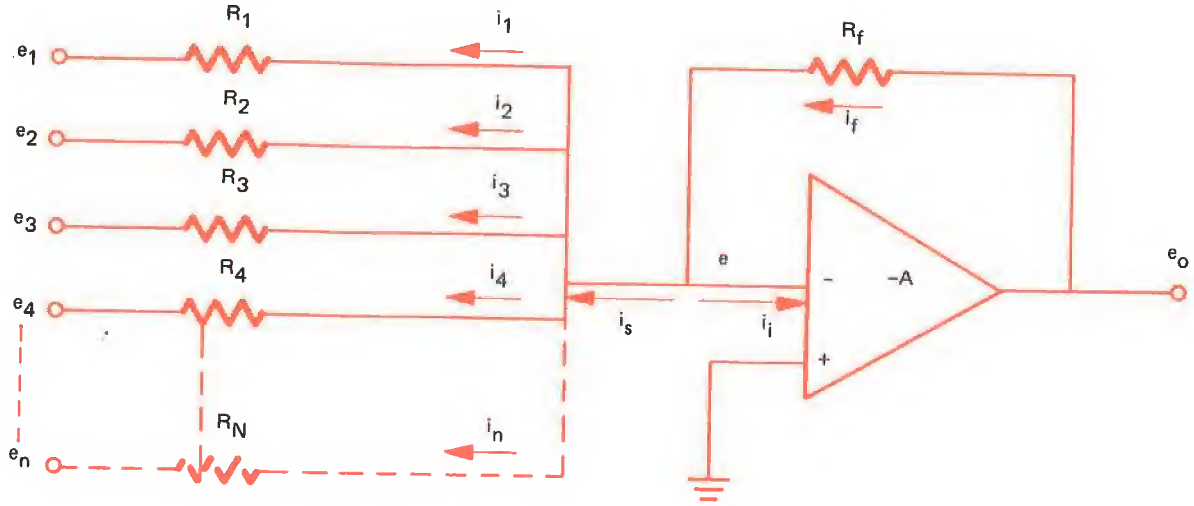


Fig. 24-4 A Summing Amplifier

Performing computations in this manner is called *electronic analog computation* and forms the basis for so-called *electronic analog computers.*

Let us now turn our attention to the circuit shown in figure 24-4. Using the same type of analysis as applied previously, we see that

$$i_s = i_1 + i_2 + i_3 + i_4 + \ldots + i_n$$

And since $e \approx 0$ (A is very large),

$$i_i = \frac{e_1}{R_1} \qquad i_3 = \frac{e_3}{R_3} \qquad i_n = \frac{e_n}{R_n}$$

$$i_2 = \frac{e_2}{R_2} \qquad i_4 = \frac{e_4}{R_4}$$

Therefore,

$$i_s = \frac{e_1}{R_1} + \frac{e_2}{R_2} + \frac{e_3}{R_3} + \frac{e_4}{R_4} + \cdots \frac{e_n}{R_n}$$

and

$$i_f = \frac{e_o}{R_f}$$

Then if $i_i \approx 0$, we have $i_f = -i_s$ or

$$\frac{e_o}{R_f} = -\frac{e_1}{R_1} - \frac{e_2}{R_2} - \frac{e_3}{R_3} - \frac{e_4}{R_4} - \cdots - \frac{e_n}{R_n}$$

Finally, multiplying through by R_f we have

$$e_o = -\frac{R_f}{R_1} e_1 - \frac{R_f}{R_2} e_2 - \frac{R_f}{R_3} e_3 - \frac{R_f}{R_4} e_4$$

$$- \cdots \frac{R_f}{R_n} e_n \qquad \textbf{(24.4)}$$

Using this relationship we may take several voltages, multiply each by a constant and sum them.

If is perhaps worth noting at this point that, if we let $R_i = R_1 = R_2 = R_3 = R_4 = \ldots = R_n$, then equation 24.4 becomes

$$\boxed{e_o = -\frac{R_f}{R_i} (e_1 + e_2 + e_3 + e_4 + \ldots + e_n)}$$

(24.5)

which, of course, shows the summation ability of the amplifier more clearly.

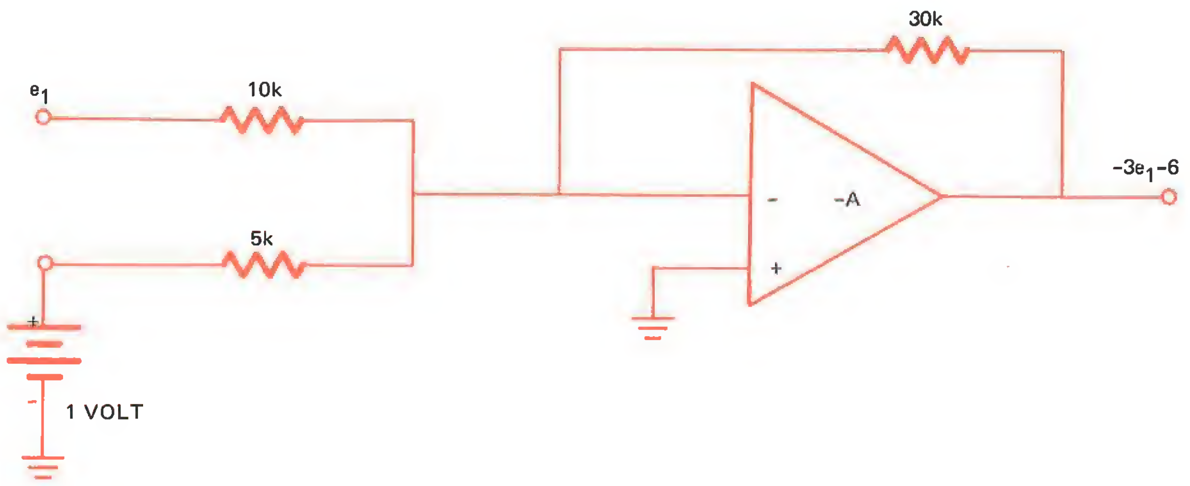


Fig. 24-5 Producing $-3e_1 -6$

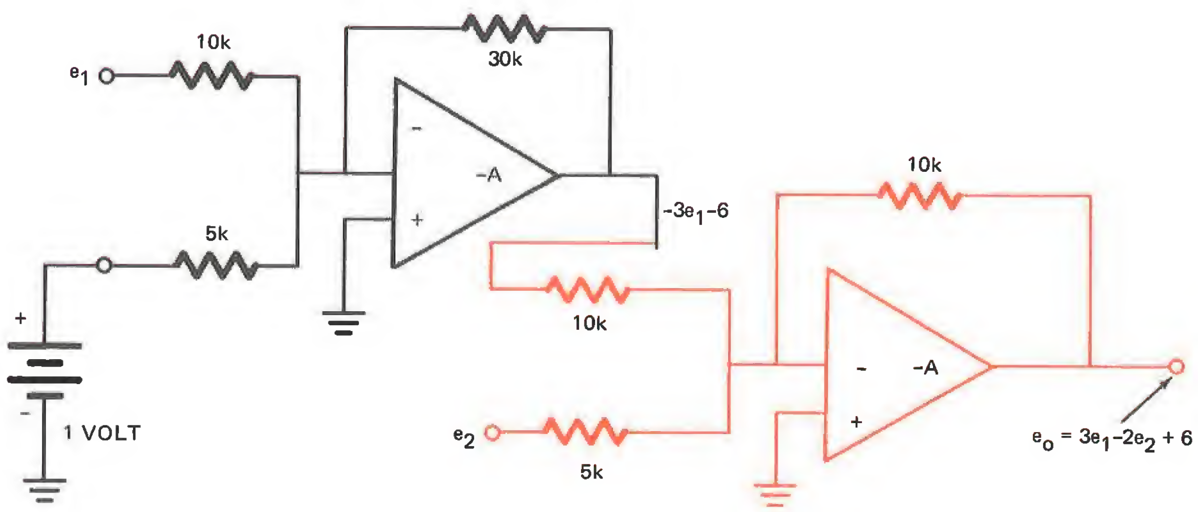


Fig. 24-6 Circuit for $e_o = 3e_1 -2e_2 + 6$

To illustrate the use of an amplifier as a summing device, let us suppose that we have two varying voltages (e_1 and e_2) and we wish to combine them in such a way that

$$e_o = 3e_1 - 2e_2 + 6 \text{ volts}$$

We may do this by first combining the two positive terms as shown in figure 24-5, and then adding in the $2e_2$ term giving the complete circuit shown in figure 24-6.

This is not the only circuit which would produce the desired results. Indeed, there are many alternate possibilities. The usual goal is to solve the problem using the smallest number of operational amplifiers.

Using analog techniques, the constant quantities can be combined in a great variety of ways.

MATERIALS

1 Variable DC power supply (0 – 90V)
1 VOM or FEM
1 Audio generator
1 Oscilloscope
1 Integrated operational amplifier type SN724 or equivalent
1 IC socket
1 Breadboard
2 1k resistors 2W
1 8.2k resistor 1/2W
1 Resistance substitution box (15 – 10 megohm 1/2W)
1 Sheet of linear graph paper
1 33k resistor 1/2W
1 4.7k resistor 1/2W
1 1.8k resistor 1/2W

PROCEDURE

1. Apply power to the operational amplifier as shown in figure 24-7.

NOTE: From this point on it will be assumed that power is properly applied as shown in figure 24-7. The power supply connections will not be indicated in the following steps.

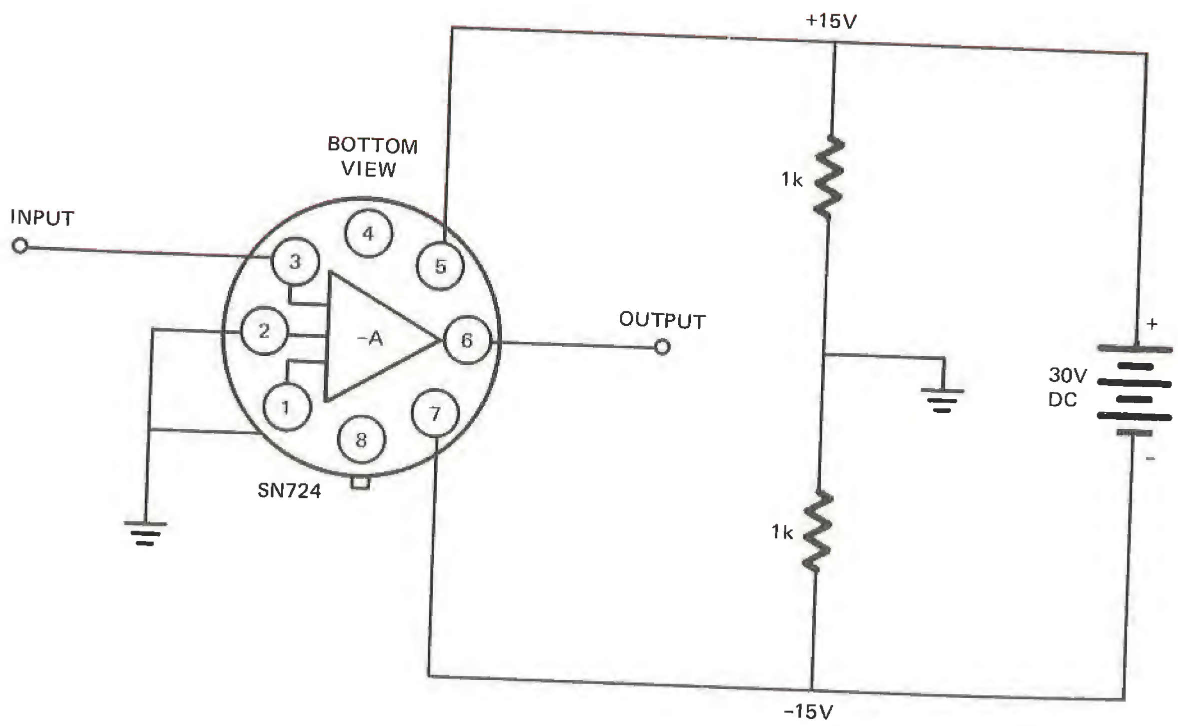


Fig. 24-7 Power Supply Connection

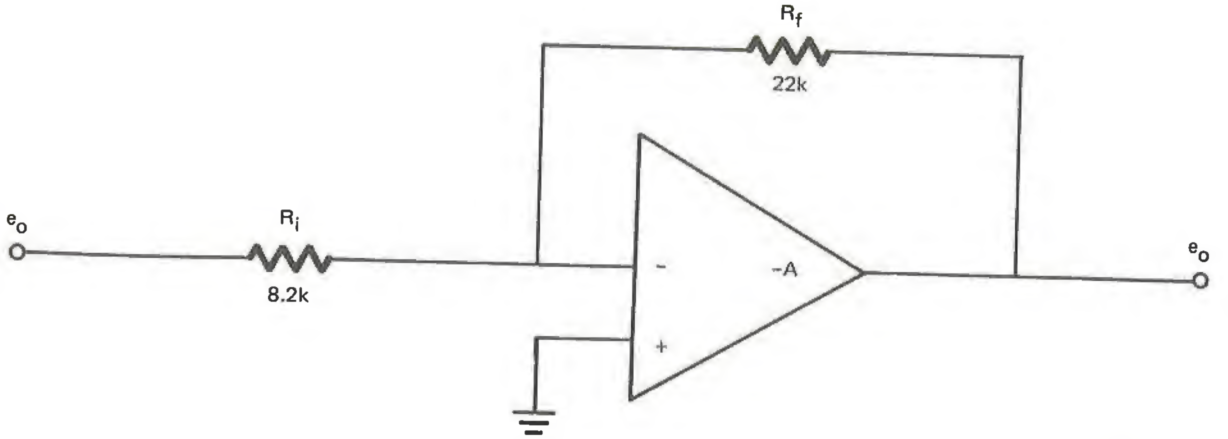


Fig. 24-8 The First Experimental Circuit

2. Compute and record the gain of the circuit shown in figure 24-8.
3. Assemble the feedback network shown in figure 24-8 using the resistance substitution box for R_f.
4. Measure and record the gain of the circuit.
5. Repeat steps 2 and 4 for resistance substitution box settings of:

(a) 470 ohms	(e) 10k	(i) 220k
(b) 1k	(f) 33k	(j) 470k
(c) 2.2k	(g) 68k	
(d) 4.7k	(h) 100k	

6. On a sheet of graph paper plot the measured gain (vertically) versus the ratio R_f/R_i (horizontally).
7. Add a second input resistor to the amplifier as shown in figure 24-9.

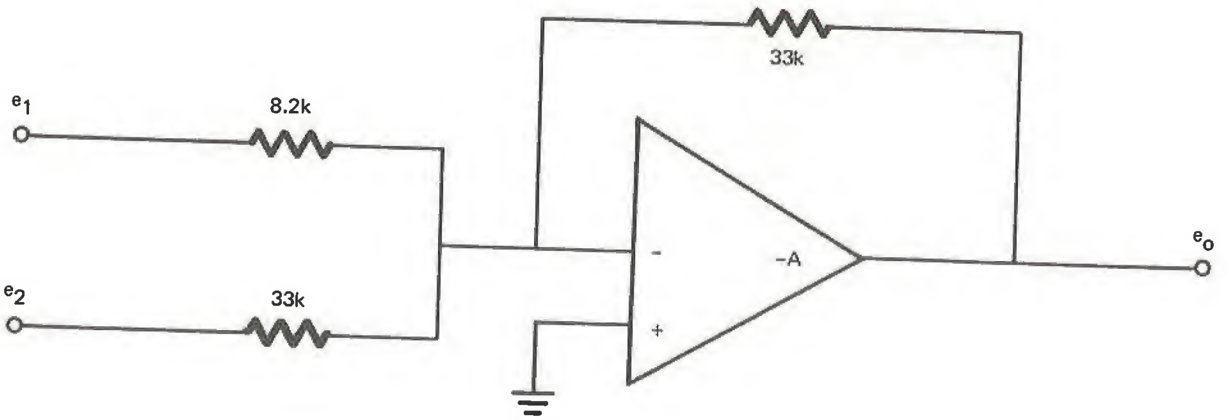


Fig. 24-9 The Second Experimental Circuit

8. Compute and record the output that would result if $e_1 = +2.77$ volts and $e_2 = -7.23$ volts.
9. Construct the source voltage divider shown in figure 24-10.
10. Connect the source to the amplifier and measure e_o.

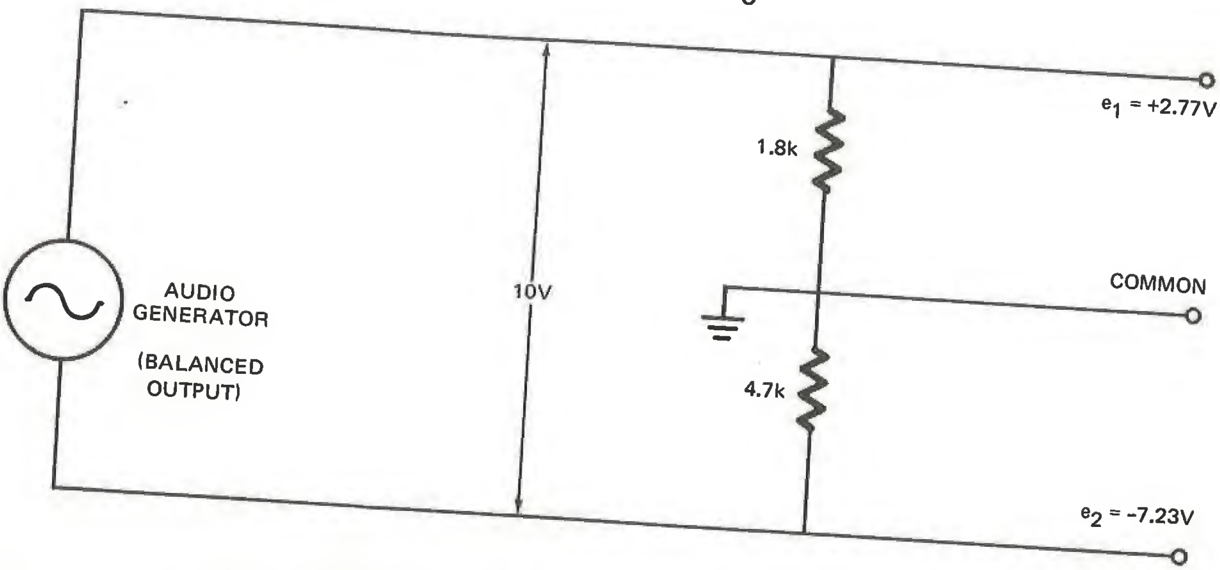


Fig. 24-10 Circuit for Producing e_1 and e_2

First Circuit

R_f Ohms	A′ Comp	A′ Meas
470		
1k		
2.2k		
4.7k		
10k		
33k		
68k		
100k		
220k		
470k		

Second Circuit

e_o Comp	e_o Meas

Fig. 24-11 The Data Tables

ANALYSIS GUIDE. In analyzing these data you should try to evaluate the validity of the circuit analysis presented in the discussion. In particular, consider the extent to which your gain calculations for the first circuit agreed with the measured values. Also, consider the agreement between the e_o values for the second circuit.

PROBLEMS

1. Draw a diagram which will produce an output of $e_o = -e_1 - 3e_2 + 2e_3 + 2$ volts when values of e_1, e_2, and e_3 are applied.
2. What equation describes the output of the circuit in figure 24-12?

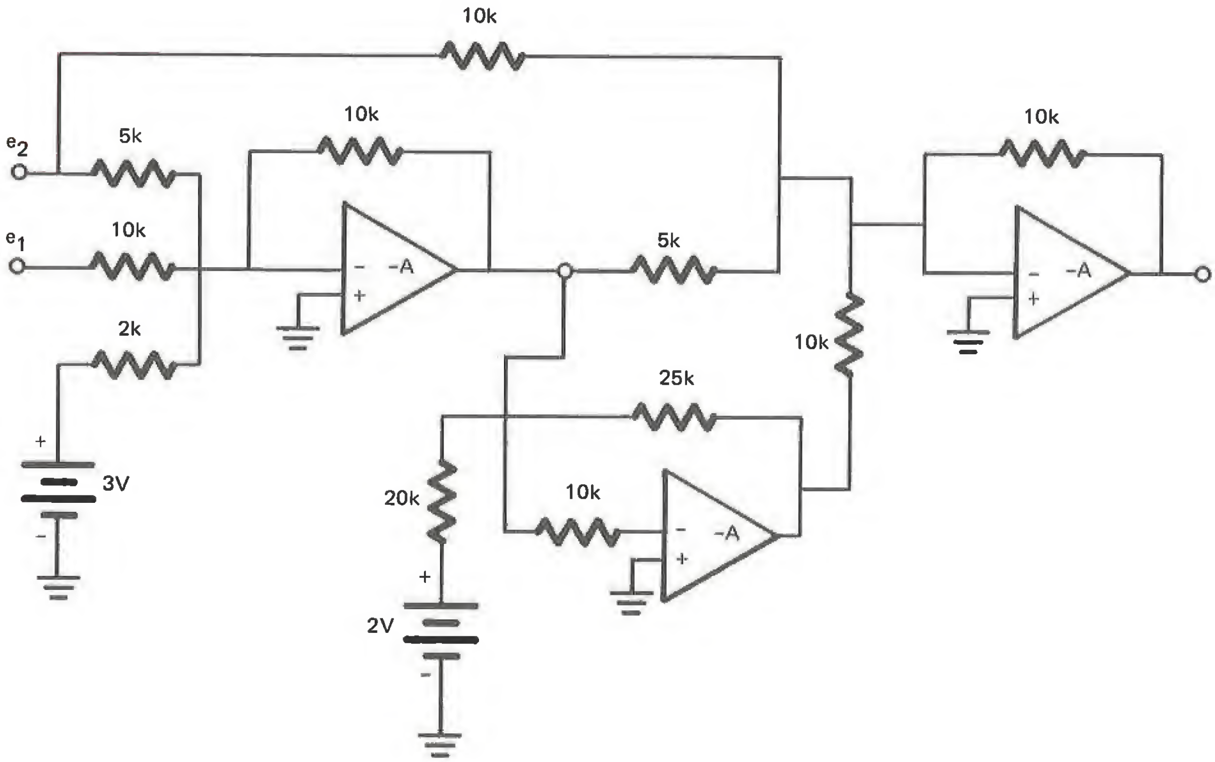


Fig. 24-12 Circuit for Problem 2

experiment 25 *INTEGRATING AMPLIFIERS*

INTRODUCTION. Operational amplifiers are widely used to perform an integrating process. In this experiment we shall examine this mode of operational amplifier operation.

DISCUSSION. Let us consider the operational amplifier circuit shown in figure 25-1.

Operational amplifiers are normally designed so that the gain (-A) is very high and the input current (i_i) is very very small. If we assume that the gain is so large that the input voltage (e) approaches zero and that i_i also approaches zero, then the feedback current becomes equal to the source current:

$$i_f = -i_s \qquad (25.1)$$

Since e = 0, then we see that

$$i_s = \frac{e_s}{R} \qquad (25.2)$$

and

$$e_c = e_o$$

The charge on the capacitor will, of course, be

$$q_c = C\, e_c$$

and because e_c and e_o are equal, we may write

$$q_c = C\, e_o$$

Differentiating each side renders

$$\frac{dq_c}{dt} = C\frac{de_o}{dt}$$

Then, since $i_f = dq_c/dt$, we may say that

$$i_f = C\frac{de_o}{dt}$$

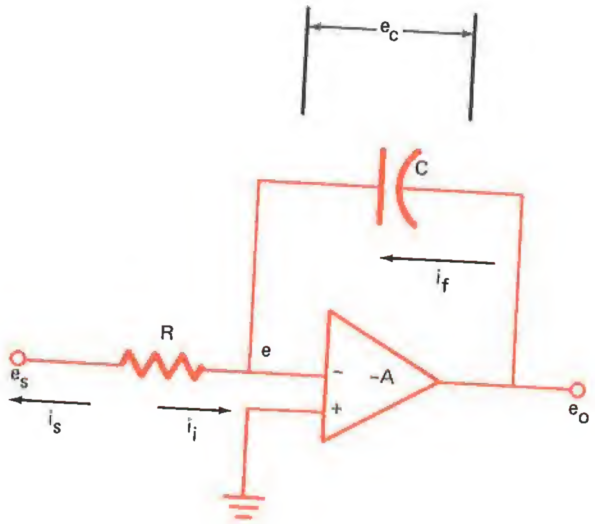


Fig. 25-1 An Integrating Amplifier Circuit

Combining this result with equation 25.1 and 25.2 gives us

$$C\frac{de_o}{dt} = -\frac{e_s}{R}$$

which we may rewrite in the form

$$de_o = -\frac{1}{RC}\, e_s\, dt$$

Finally, taking the integral of each side provides

$$\boxed{e_o = -\frac{1}{RC}\int e_s\, dt} \qquad (25.3)$$

or, in other words, the output of the amplifier in figure 25-1 is directly proportional to the integral of the input signal. For this reason we call the circuit an integrating amplifier.

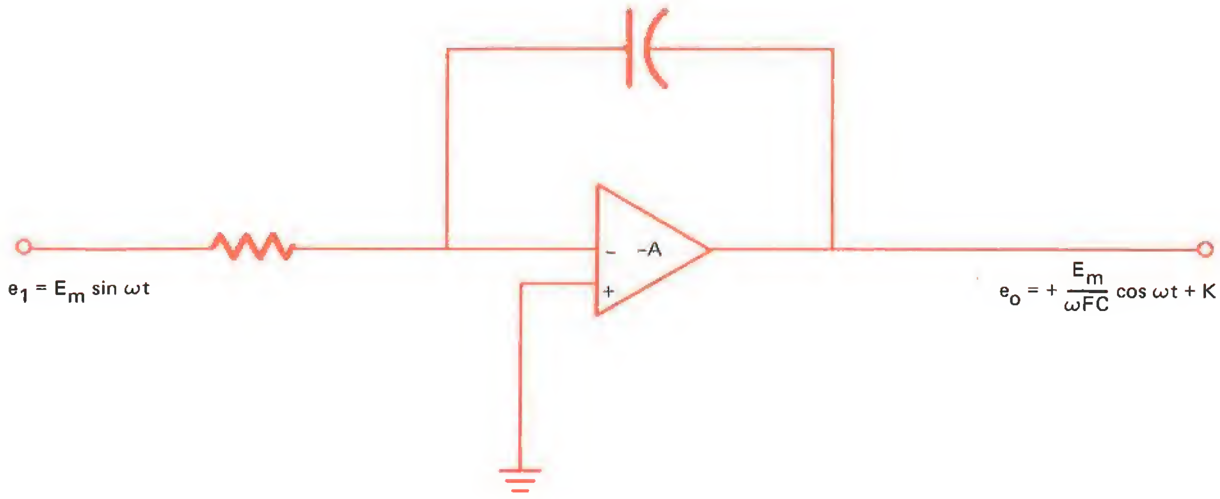


Fig. 25-2 Integrating $E_m \sin \omega t$

The integrating amplifier shown in figure 25-1 is sometimes used as a 90° phase shifter. Let us suppose that we have a *sinusoidal* voltage represented by

$$e_1 = E_m \sin \omega t$$

and we wish to shift its phase by 90° to create

$$e_2 = E_m \cos \omega t$$

The circuit shown in figure 25-2 will produce an output of

$$e_o = -\frac{1}{RC}\int E_m \sin \omega t \, dt = +\frac{E_m}{\omega RC} \cos \omega t + K$$

where K is the constant of integration and will equal zero if there is no initial change on the capacitor. Then, by multiplying by the appropriate constant as shown in figure 25-3, we have the desired result.

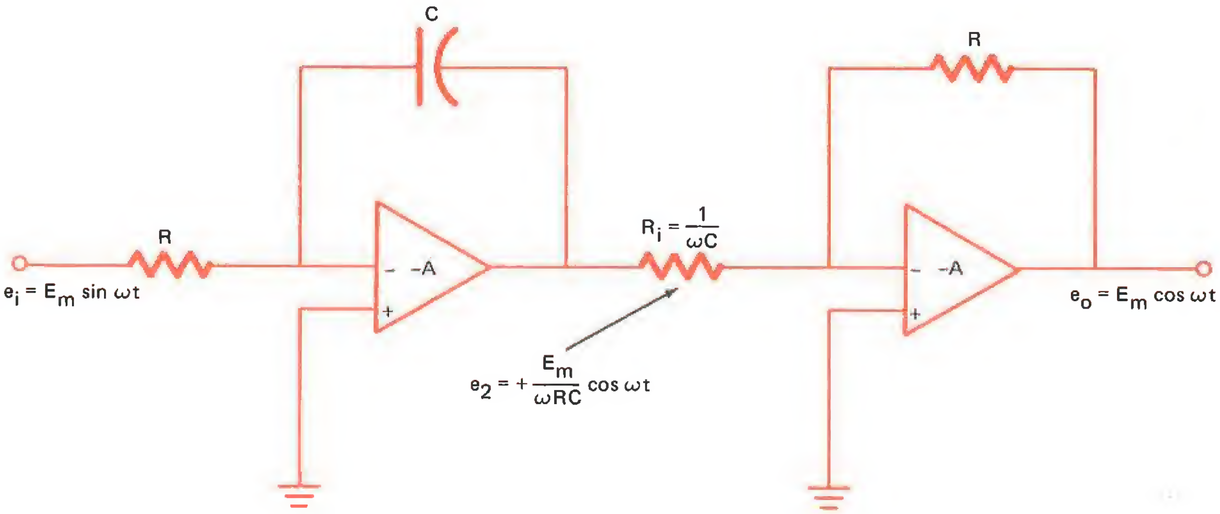


Fig. 25-3 Generating $e_o = E_m \cos \omega t$

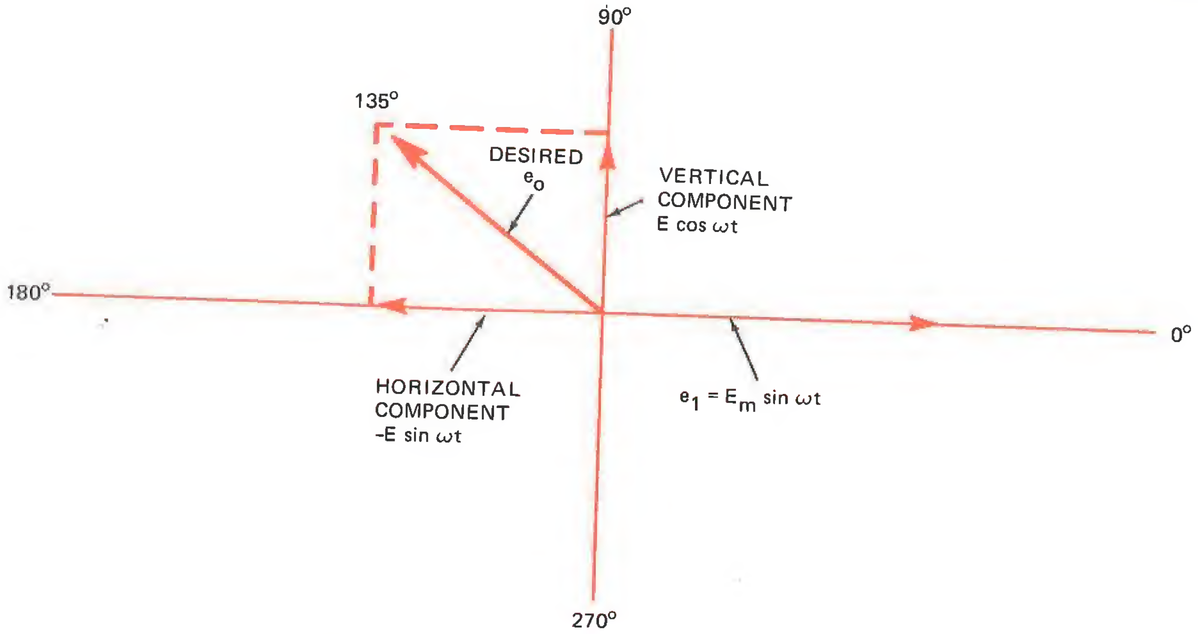


Fig. 25-4 Resolving e_o Into Its Components

By using this phase shift capability of an integrating amplifier it is possible to build a phase shifter to provide any desired amount of phase shift from 0° to 360°. For example, let us consider how a sine wave ($e_1 = E_m \sin \omega t$) may be shifted by 135°. If we draw a vector diagram of the original voltage and the desired output it would appear as shown in figure 25-4, and we see that e_o can be resolved into horizontal and vertical components of $-E \sin \omega t$ and $E \cos \omega t$, respectively. If we generate these two components and add them, we will have the desired output.

Figure 25-5 shows a circuit for producing the 135° phase-shifted sinusoid. Indeed, by adjusting R_2 and R_3 in this circuit (also R_1 and C), we may adjust the phase of the output from 90° to 180° with respect to the input voltage. Also by adjusting R_f we may control the output level while holding the phase shift constant.

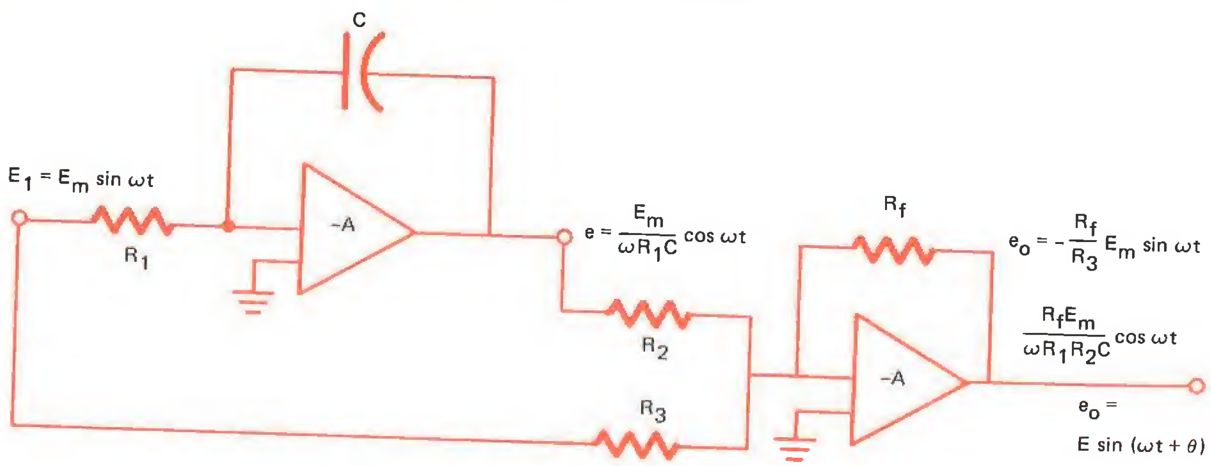


Fig. 25-5 Circuit for 90°-180° Phase Shifting

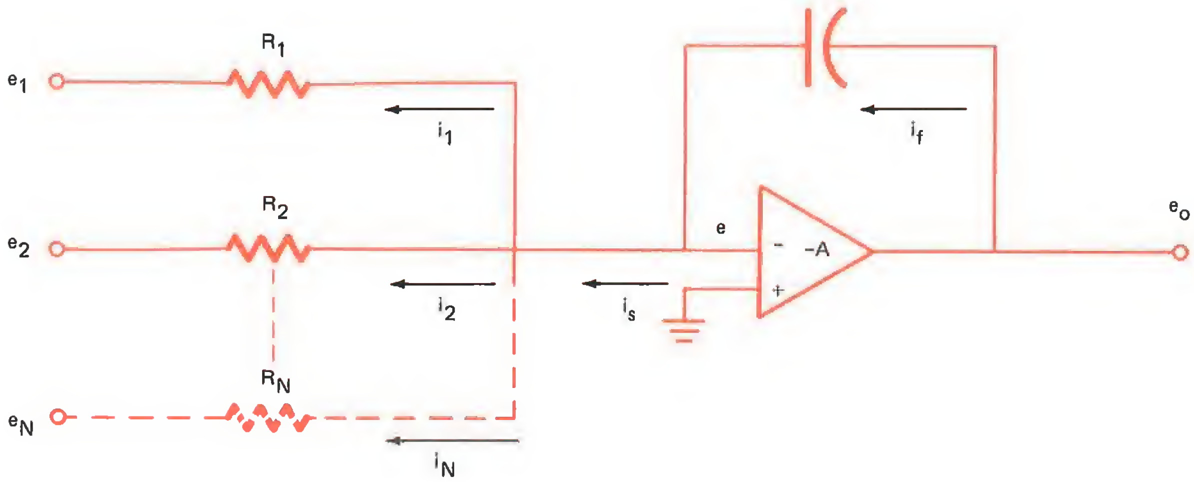


Fig. 25-6 A Summing Integrator

Integrating amplifiers are not limited to a single input. They can, in fact, have any reasonable number as indicated in figure 25-6. In analyzing this circuit we assume (as before) that

$$i_f = -i_s$$

And we observe that

$$i = i_1 + i_2 + \dots + i_n$$

Therefore (since e is assumed to approach zero)

$$i_s = \frac{e_1}{R_1} + \frac{e_2}{R_2} + \dots + \frac{e_n}{R_N}$$

On the other hand, i_f is, as before, equal to

$$i_f = C\frac{de_o}{dt}$$

As a result we may write

$$C\frac{de_o}{dt} = -\frac{e_1}{R_1} - \frac{e_2}{R_2} - \dots - \frac{e_N}{R_N}$$

and

$$de_o = -\frac{1}{R_1C}e_1\,dt - \frac{1}{R_2C}e_2\,dt - \dots - \frac{1}{R_NC}e_N dt$$

Then integrating both sides renders

$$\boxed{e_o = -\frac{1}{R_1C}\int e_1 dt - \frac{1}{R_2C}\int e_2 dt - \dots - \frac{1}{R_NC}\int e_n dt} \qquad \textbf{(25.4)}$$

From this equation we see that the circuit in figure 25-6 provides an output which is proportional to the *sum of the integrals of the inputs.* Such a circuit is called a *summing integrator.*

Integrators may be used for several things other than phase shifting. For example, suppose we wish to generate an output such that

$$E_o = t^2 - 3t + 2 \text{ volts} \qquad \textbf{(25.5)}$$

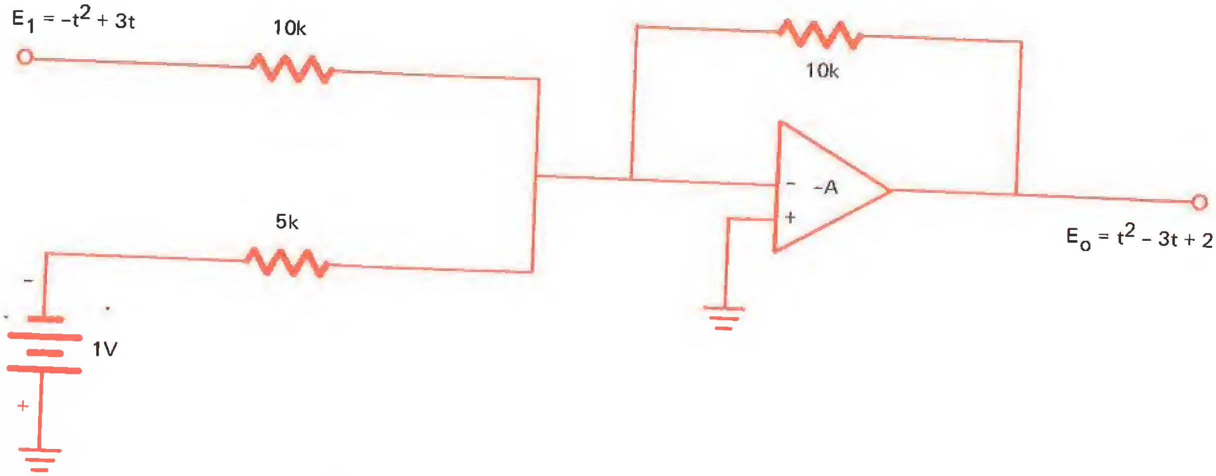


Fig. 25-7 Establishing the Constant Term

To achieve this result we *pretend* that we have the desired function at the output of a system. Then we draw a circuit which will provide the necessary *constant term* (+2 in this case) and determine the required variable input to this stage. See figure 25-7.

Next we differentiate the variable terms to determine what input would be required for an integrator to produce the desired signal

$$\frac{dE_1}{dt} = -2t + 3$$

At this point we must multiply by (−1) to allow for the inversion of the integrator. We now have $2t - 3$ as the input of the integrator. We now add this portion of the circuit as seen in figure 25-8. With this stage installed we repeat the differentiating process outlined before using the remaining variable term (s)

$$E_2 = t, \frac{dE_2}{dt} = 1, -\frac{dE_2}{dt} = -1$$

And we connect another integrator having an input of −1 volt as shown in figure 25-9.

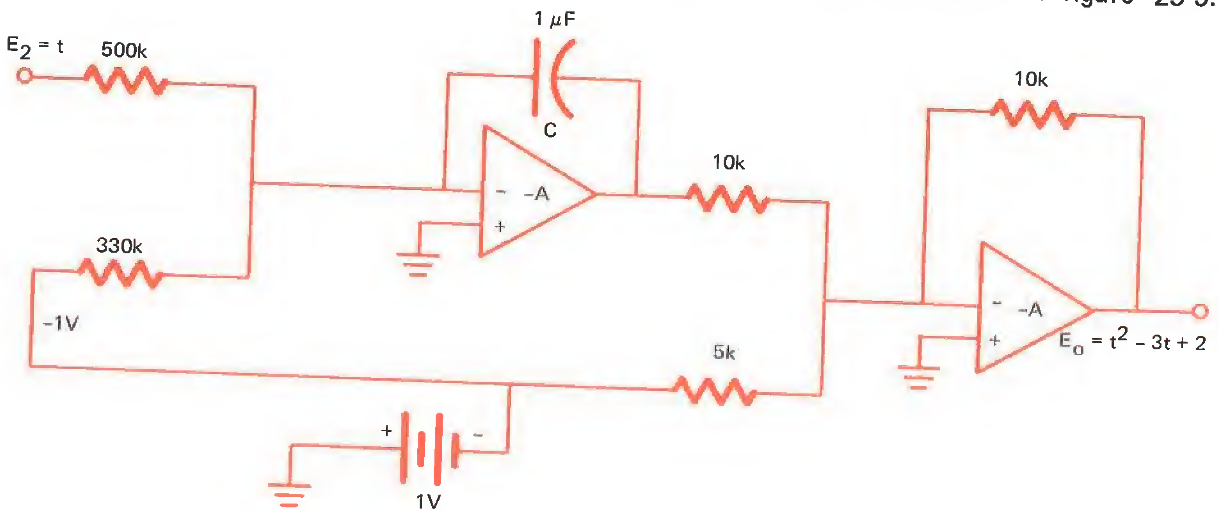


Fig. 25-8 Adding the First Integrator Stage

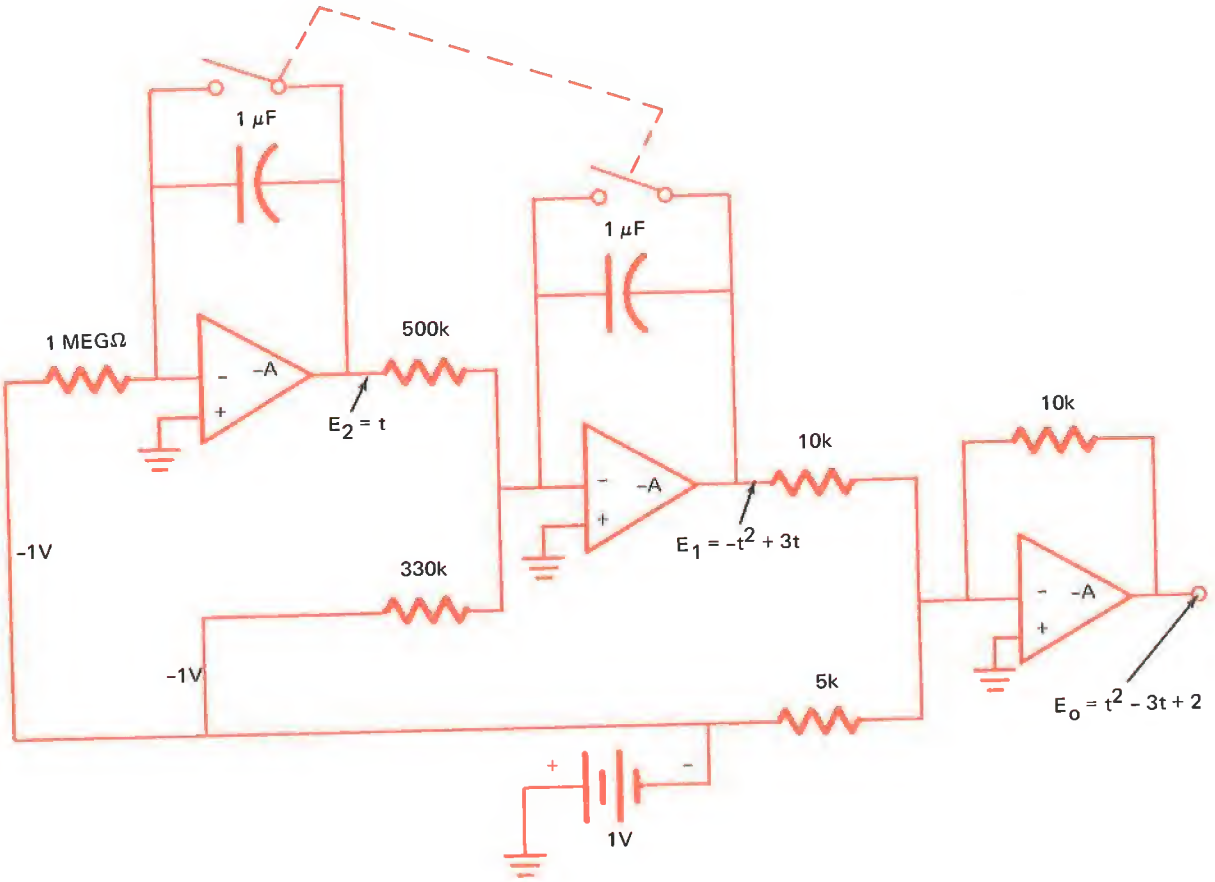


Fig. 25-9 Complete Circuit for Generating $E_o = t^2 - 3t + 2$

One additional feature is also included in the diagram, the switches connected across the integrating capacitors are for the purpose of turning the function generator on and off. They also insure that the initial charge on the capacitors is zero.

There are many other uses of operational amplifiers in general and integrating amplifiers in particular, but to explore them further would be beyond the scope of this experiment.

MATERIALS

1 Variable DC power supply (0 – 40V)
1 Audio generator
1 VOM or FEM
1 Oscilloscope
1 Integrated operational amplifier type SN724 or equivalent
1 Set of data sheets for the above IC
1 Breadboard
2 1k resistors 2W
1 IC socket
1 Resistance substitution box (15 – 10 meg 1/2W)
1 10 µF 600W VDC oil-filled capacitor
1 1 µF 600W VDC oil-filled acpacitor
1 1.6 volt battery
2 Sheets of linear graph paper

PROCEDURE

1. Connect the power supply to the operational amplifier in the manner prescribed by the manufacturer's data sheet.
2. Set up the operational amplifier as an integrator using C = 10 μF, and R = 1 megohm (use the resistance substitution box for R).
3. Connect the audio generator to the input of the integrator. Set the frequency to 10 Hz and view the output waveform with the oscilloscope.
4. Make sketches of the input and output signal showing the relative phase and amplitude.
5. Change C to 1 μF and repeat steps 3 and 4.

R (ohms)	1 meg	680 K	470 K	330 K	220 K	100 K
E_O (volts)	T (Sec)	T (Sec)	T (Sec)	T (Sec)	T (Sec)	T (Sec)
0.5						
1.0						
1.5						
2.0						
2.5						
3.0						
3.5						
4.0						
4.5						
5.0						
5.5						
6.0						
6.5						
7.0						
7.5						
8.0						
8.5						

Fig. 25-10 The Data Table

6. Change R to 100k and repeat steps 3 and 4.
7. Return the amplifier to the conditions set in step 2.
8. Connect the 1.6 volt battery to the input.
9. Short circuit the capacitor. Set the oscilloscope for: 1 volt per CM and 1 second per centimeter. When the trace is on the left of the screen and on a vertical line, remove the short on the capacitor and observe the trace of the oscilloscope.
10. Make a sketch of the trace observed on the oscilloscope, recording the amplitude. (Let the trace run for approximately five to eight seconds.)
11. Change the value of R to 100k and repeat step 10.
12. Similarly repeat step 9–10 for resistance values of 10k, 1k, and 0.1k.

ANALYSIS GUIDE. In the analysis of your results from this experiment you should be chiefly concerned with evaluating the effectiveness of the amplifier as an integrator. To this end you could plot the integrals of the two functions used and compare them to your plots of the results.

PROBLEMS

1. Draw a block diagram of an electronic phase shifter which will shift the phase of an input sinusoid 300 degrees. Show all operational component values.
2. Draw a function generator diagram which would produce an output of $e_o = 6t^2 + 4$ volts. Show all operational component values.
3. What equation describes the output voltage of the system shown in figure 25-11?
4. Draw a circuit using fewer operational amplifiers which will generate the function in problem 3.

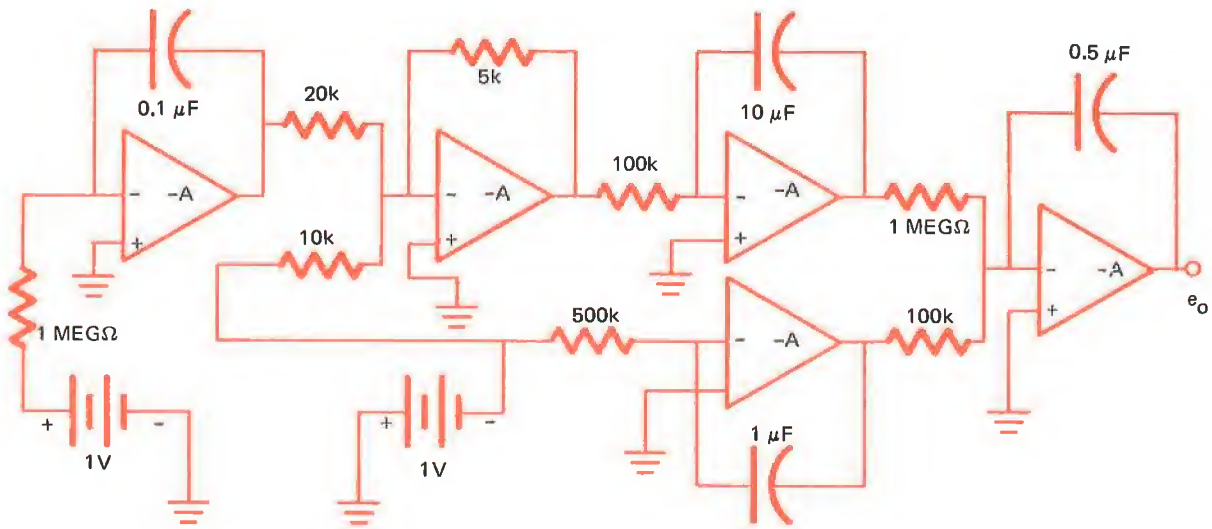


Fig. 25-11 Circuit for Problem 3

experiment 26 CHOPPER MODULATORS

INTRODUCTION. Synchronous modulators are frequently used in electronic systems where a DC signal is to control the amplitude and phase of an AC signal. Many systems use them to chop up a DC signal so that it can be amplified by an AC amplifier. In this experiment we will examine some examples of modulator circuitry and operation.

DISCUSSION. Modulators are devices used to convert DC electrical signals into AC signals. The output amplitude of the AC must vary with the amplitude of the input DC and the phase must shift by 180 degrees if the polarity of the DC reverses. Modulators are used where DC control signals in a system must be converted and amplified by an AC amplifier for use with AC-operated devices such as AC servomotors.

Sometimes it is also necessary to convert an AC signal to DC with polarity reversals of the DC for 180 degree phase shifts of the AC. When the necessity of reversing the output voltage exists, an ordinary power supply rectifier cannot be used. Circuits that can accomplish this function are called *demodulators.*

One type of modulator is shown in figure 26-1. It is an electromechanical switching device called a *chopper.* Notice that the chopper reed is balanced between the poles of a magnet. If we apply an alternating current to the coil, the reed tip will be alternately magnetized by the coil field. When the reed tip is an induced north pole, it will turn to the right, making the righthand contacts and breaking the lefthand ones. During the next half of the coil current cycle, the reed will be an induced south pole. Now

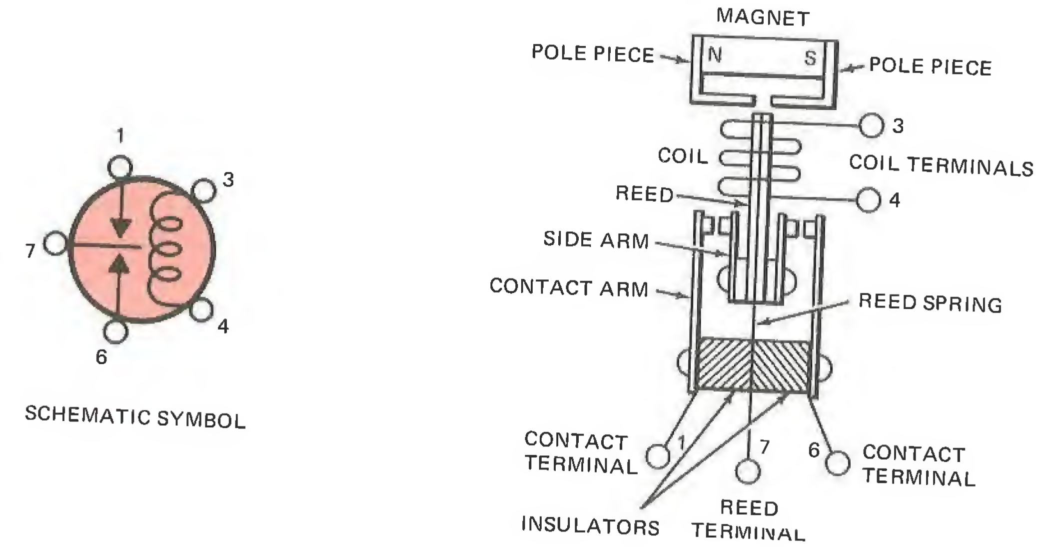


Fig. 26-1 An Electromechanical Contact Modulator

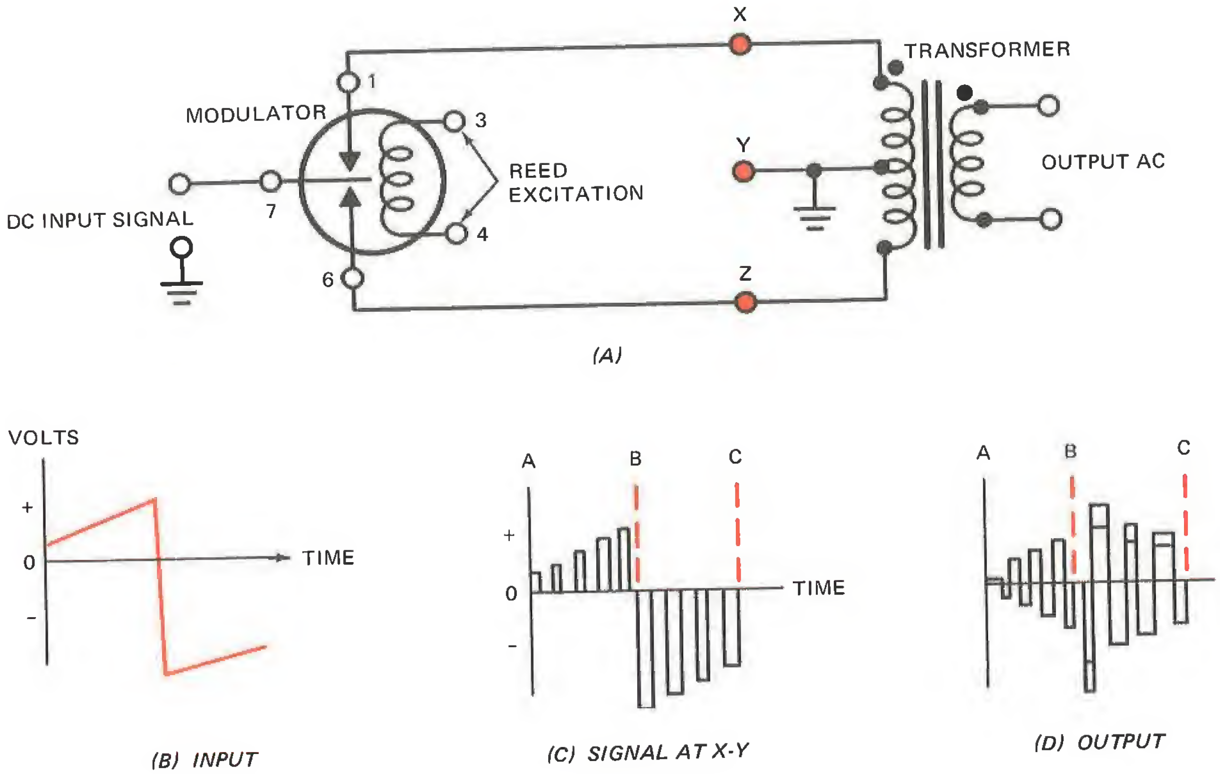


Fig. 26-2 A Modulator Circuit

it will swing to the left, making the left contacts and breaking the righthand ones.

In other words, the chopper operates like a motor-driven switch which is synchronized with the alternating coil current.

Figure 26-2 shows how a chopper can be used in an electromechanical modulating circuit. The vibrating reed chops up the DC input signal into a rectangular wave AC signal.

The input signal of figure 26-2 is shown as a DC control signal which can change in amplitude and polarity depending upon changes in the system from which the signal is taken. While it may seem odd to you that we are discussing a DC signal and then speak of it changing with time, keep in mind that the time axis here may be calibrated in hours or even days. The DC control signal will remain at a fixed voltage if the system being monitored does not change. In other words, for any *given* condition of the *source,* input voltage is a steady DC value, but the level can change if the source changes.

Again directing your attention to figure 26-2(a), when the input signal is a particular DC value, the vibrating reed connects this voltage between points X and Y when it is up. When the reed is down, this same voltage is applied between Z and Y. The frequency would vary with the excitation frequency of the reed and the output voltage amplitude would vary with the input signal level.

The same voltage is applied to points X-Y and Z-Y by the switching action of the vibrating reed. However, you will observe that the direction of the current is first up then down through the primary of the trans-

former resulting in the output signal shown in figure 26-2(d). Observe the amplitude changes of the output as time varies along the time axis from A to B and from B to C. Also, note the phase change that takes place at B when the polarity of the input reverses.

The ring modulator is a circuit in which the mechanical vibrator is replaced by semiconductor diodes. The diodes are used as switches and are controlled by the excitation voltage.

The circuit of a ring modulator is shown in figure 26-3. When the excitation voltage is such as to make point A positive with respect to point B, diodes D_1 and D_2 are forward-biased by current from the excitation transformer. In this condition the DC input signal is applied from the center tap of the excitation transformer through D_1 and the bottom half of the output transformer. The current direction will depend on the polarity of the DC input.

As you probably have already figured out, the other half cycle of the excitation voltage will turn on diodes D_3 and D_4, applying the input DC signal current through D_3 to the top half of the output transformer. Note that the DC input was alternately applied to the top and then bottom of the output transformer in exactly the same way as with the electromechanical modulator circuit. As before, the phase of the output will reverse with a reverse in the polarity of the DC input signal. This phase is normally compared to the line signal used for excitation.

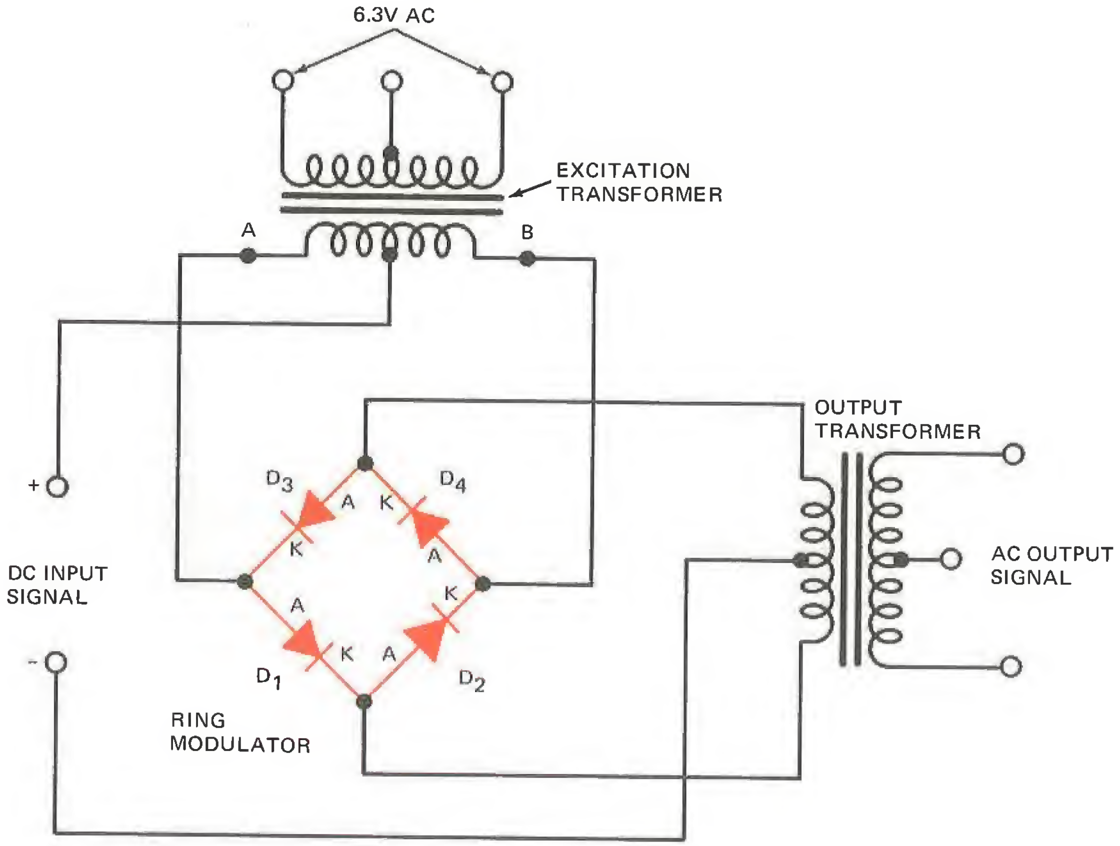


Fig. 26-3 Ring Modulator Circuitry

MATERIALS

1 Output transformer (100Ω ct – 4/8/16Ω)
4 Diodes type 1N270 or equivalent
1 Input transformer (500Ω ct – 200Ω ct)
1 560 ohm 2W resistor
2 10 ohm 2W resistors
1 DC power supply (0 – 40V)
1 Oscilloscope
1 Variable transformer (0 – 130V AC)
1 VOM or FEM

PROCEDURE

1. Connect the circuit of figure 26-4.
2. Starting at zero, carefully adjust the variable transformer for 6V AC across the input transformer secondary.
3. Connect the DC power supply to the input with the polarity indicated.

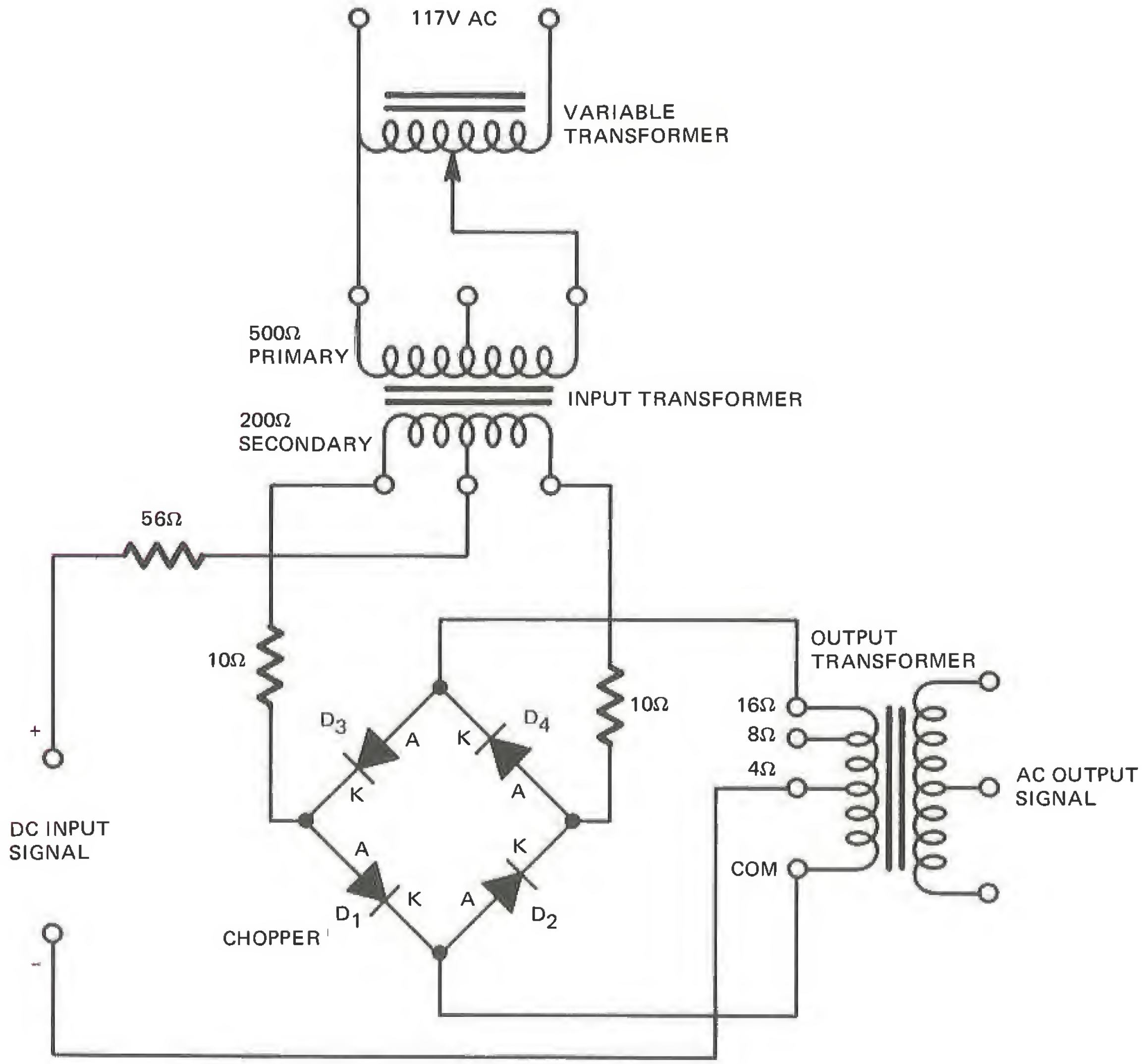


Fig. 26-4 The Experimental Circuit

4. Vary the input voltage from 0 to 20 volts in 5-volt steps. Observe and record one full cycle of the output voltage and phase using your oscilloscope. Remember you cannot use internal sync to observe phase. Since you are using 60 Hz excitation, you can use "line" synchronization. Check with your instructor if you don't know how to use line sync.

5. Reverse the leads of the DC power supply and repeat step 4 above.

Input DC Voltage	Output Signal (Show Amplitude and Phase)
0	+ 0 –
5	+ 0 –
10	+ 0 –
15	+ 0 –
20	+ 0 –
0	+ 0 –
-5	+ 0 –
-10	+ 0 –
-15	+ 0 –
-20	+ 0 –

Fig. 26-5
The Data Table

ANALYSIS GUIDE. Give a detailed explanation of the circuit operation including how the phase of the output is reversed by reversing the DC input signal. Explain any distortion observed and its probable cause.

PROBLEMS

1. Sometimes DC signals are converted to AC in order to use AC amplifiers instead of direct-coupled amplifiers. Why?
2. The AC signal from the ring modulator is ultimately to be fed to one phase winding of a two-phase motor while the other phase winding is excited by the 60 Hz line. Draw the system and explain what happens to the motor as the polarity of the DC input to the ring modulator is reversed?
3. Suppose the output of the ring modulator is to be amplified by an AC amplifier, then fed to a DC motor. What device would be necessary between the amplifier and motor?
4. What are some advantages of the circuit investigated compared to the mechanical device explained in this discussion?
5. Price out the experimental circuit and the one in figure 26-2 and compare them.

experiment 27 CHOPPER-MODULATED AMPLIFIERS

INTRODUCTION. Choppers or synchronous switches are sometimes used as modulators for AC amplifiers. In this experiment we will examine a simple example of a chopper-modulated amplifier.

DISCUSSION. Many amplifier input transducers provide a slowly varying low level DC output. Thermocouples, for example, typically produce a few millivolts of DC output that changes relatively slowly.

One way of amplifying such a signal is to employ direct-coupled amplifier stages. When this is done we must immediately become concerned with amplifier drift.

Drift is any change in amplifier characteristics which causes the DC output to change. To illustrate the problem, let's consider the system shown in figure 27-1. Suppose that the input transducer produces a 1mV DC signal and that the direct-coupled amplifier has a voltage gain of 1000. Under these conditions the recorder *should* see a one-volt signal.

Now suppose that due to a change in the surrounding temperature one of the amplifier stages shifts its Q-point, causing the DC output voltage to decrease by ten percent. The recorder will now see a voltage of 0.9 volts. By looking at the recorder record we would think that the thermocouple signal had changed when, in fact, it was a DC level inside the amplifier changing.

We call the error caused by the change in DC level a drift signal. This kind of measurement drift is very troublesome in instrumentation systems. If the amplifier has a relatively high gain, then a very small DC level change in an early stage can cause a very large change in the output level.

There are several ways that drift can be reduced. Using negative feedback around the amplifier is one way. Another way is to use an AC amplifier and convert the input signal to an AC quantity. This process of converting a DC signal to an AC one for amplification is called chopping or modulating the signal. Figure 27-2 shows a complete system of this type.

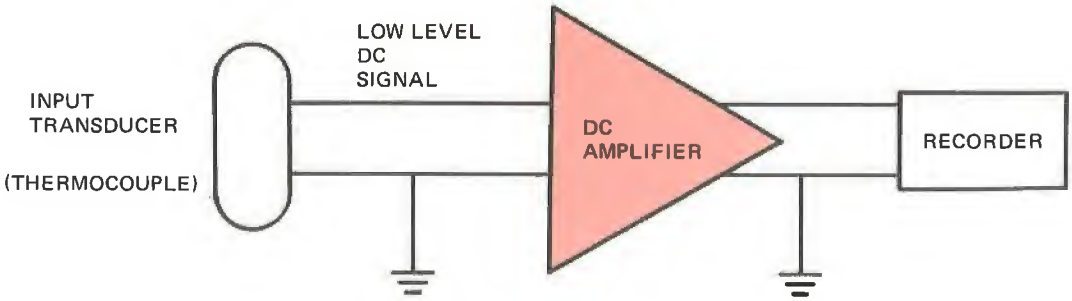


Fig. 27-1 An Amplifier System

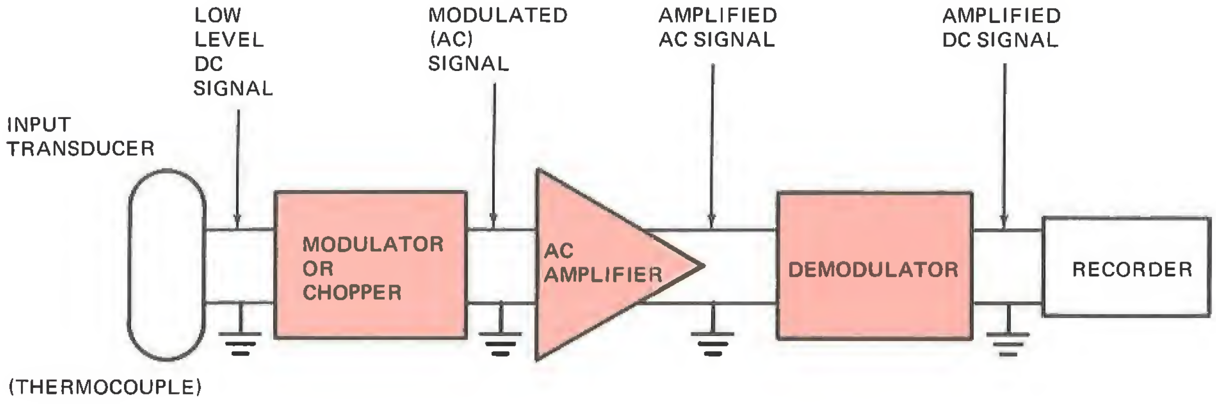


Fig. 27-2 A Modulated Amplifier System

In this system the low level DC signal is converted to an AC signal by the modulator. Then the AC signal is amplified. Finally the AC signal is converted back to a DC signal (demodulated) by the demodulator section and fed to the recorder.

The important thing to notice is that the amplifier handles only AC signals. Consequently any DC changes inside the amplifier can be prevented from reaching the recorder.

The modulator or chopper used between the input transducer and the amplifier may be either of two types: electromechanical or electronic. The electromechanical type chopper is usually a balanced armature synchronous vibrator somewhat as shown in figure 27-3. An AC excitation voltage is applied to the coil. This excitation is usually 6.3 VAC at 60 Hz. However, some units are designed to operate at 50 Hz, 100 Hz and 400 Hz with a variety of voltages.

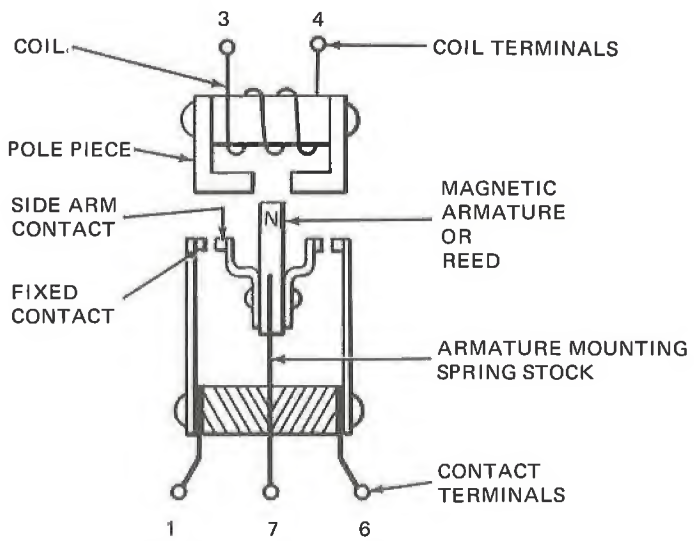


Fig. 27-3 An Electromechanical Chopper

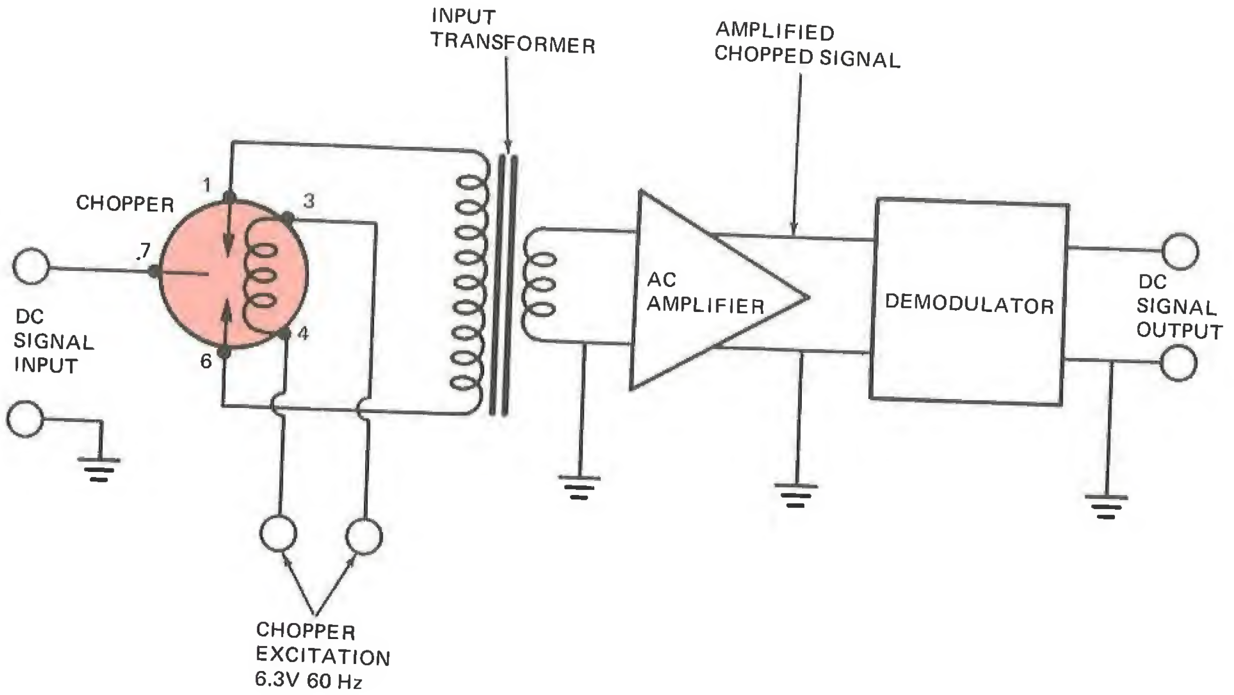


Fig. 27-4 A Chopper-Modulated Amplifier

The excitation voltage temporarily magnetizes the pole pieces in synchronization with the excitation frequency. Consequently, the pole pieces alternate between being north and south magnetic poles.

The permanently magnetized armature (some units use permanent magnet pole pieces and induced armature poles but the operation is substantially the same) is magnetically moved first to one side, then to the other.

The side arm contacts move from side-to-side with the armature and alternately contact the fixed contacts. This action produces a switching action that is synchronized with the excitation signal. This switching action is used to modulate (or chop) the amplifier input signal. Figure 27-4 shows a typical circuit diagram of a chopper-modulated amplifier.

Let's suppose that the DC input signal is a slowly varying voltage of about one volt. The chopper alternately connects this input signal to the top and bottom of the input transformer. Consequently, the transformer "sees" what is substantially a rectangular wave whose frequency is the same as the chopper excitation signal (60 Hz, in this instance).

The amplifier stage amplifies this square wave AC signal and it is subsequently demodulated (converted back to a DC level) after amplification.

We will look closer at demodulation later. Right now, let's observe that modulation in this sense is a process of alternate switching. There are several electronic circuits which are also used to perform this function. Figure 27-5 shows several of them.

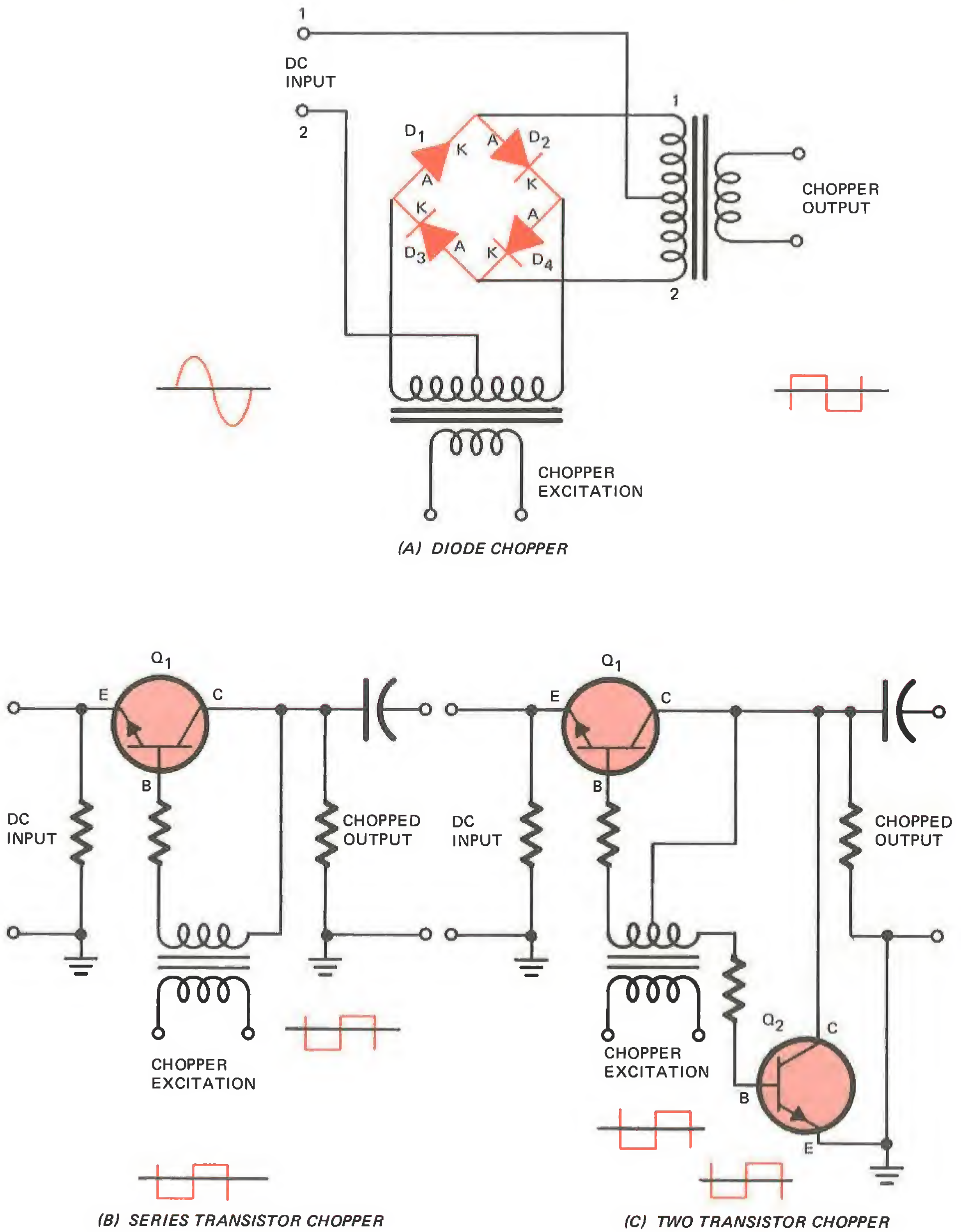


Fig. 27-5 Electronic Choppers

The first of these (figure 27-5a) is a diode chopper or *ring modulator.* The chopper excitation turns on diodes D_1 and D_2 on one half of its cycle, connecting input 2 to terminal 1 of the input transformer. During the alternate half cycle, diodes D_3 and D_4 are on, connecting input 1 to terminal 2 of the transformer. As in the case of the electromechanical chopper, a substantially square wave is produced.

Figures 27-5b and 27-5c are transistor choppers requiring a square wave excitation. In figure 27-5b the square wave simply turns Q_1 on and off producing a chopping action. A sinewave excitation can be used when the shape of the chopped output need not be square. In some very precise cases, the leakage current, I_{CO}, through Q_1 causes a small DC output when it is turned off that is troublesome. In such cases, the circuit in figure 27-5c maybe used. It not only offsets errors created by I_{CO} and the saturation V_{CE} of Q_1, but also insures an input resistance that is very low (usually below 50 ohms). This makes it particularly useful with low resistance transducers.

After the chopped signal has been suitably amplified it must be demodulated (converted back to a DC value). As was the case with the modulation process, demodulation may be by either electronic or electromechanical means.

Electronic demodulation is usually accomplished by employing a rectifier and filter of some type. Figure 27-6 shows the generalized case.

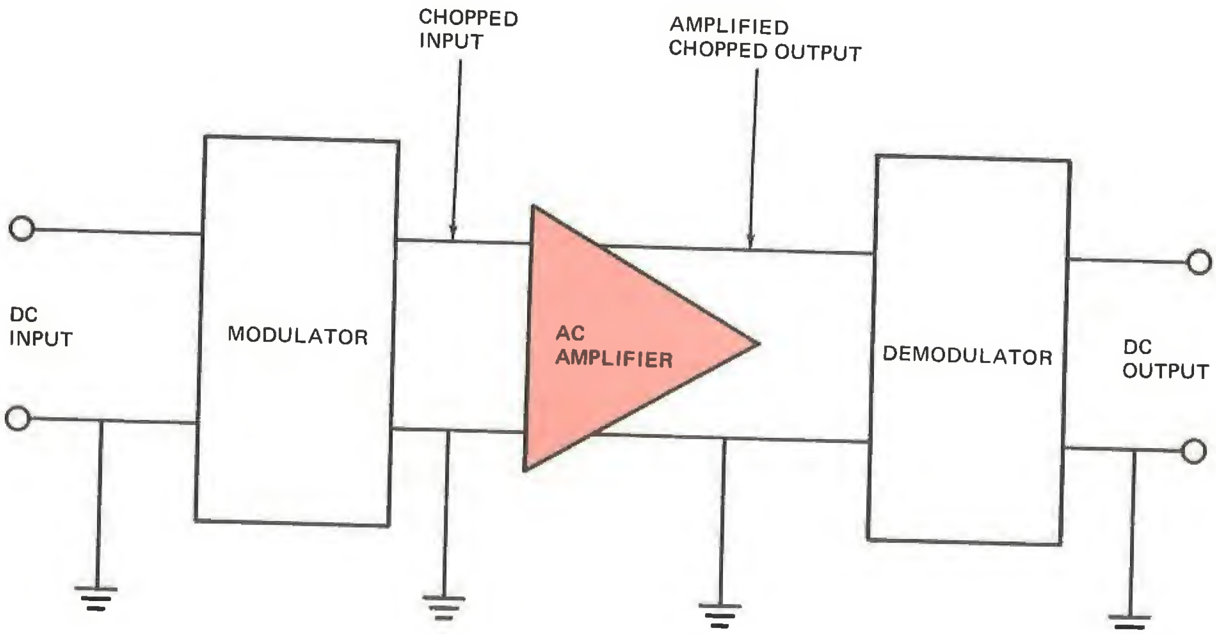


Fig. 27-6 A Chopped DC-to-DC System

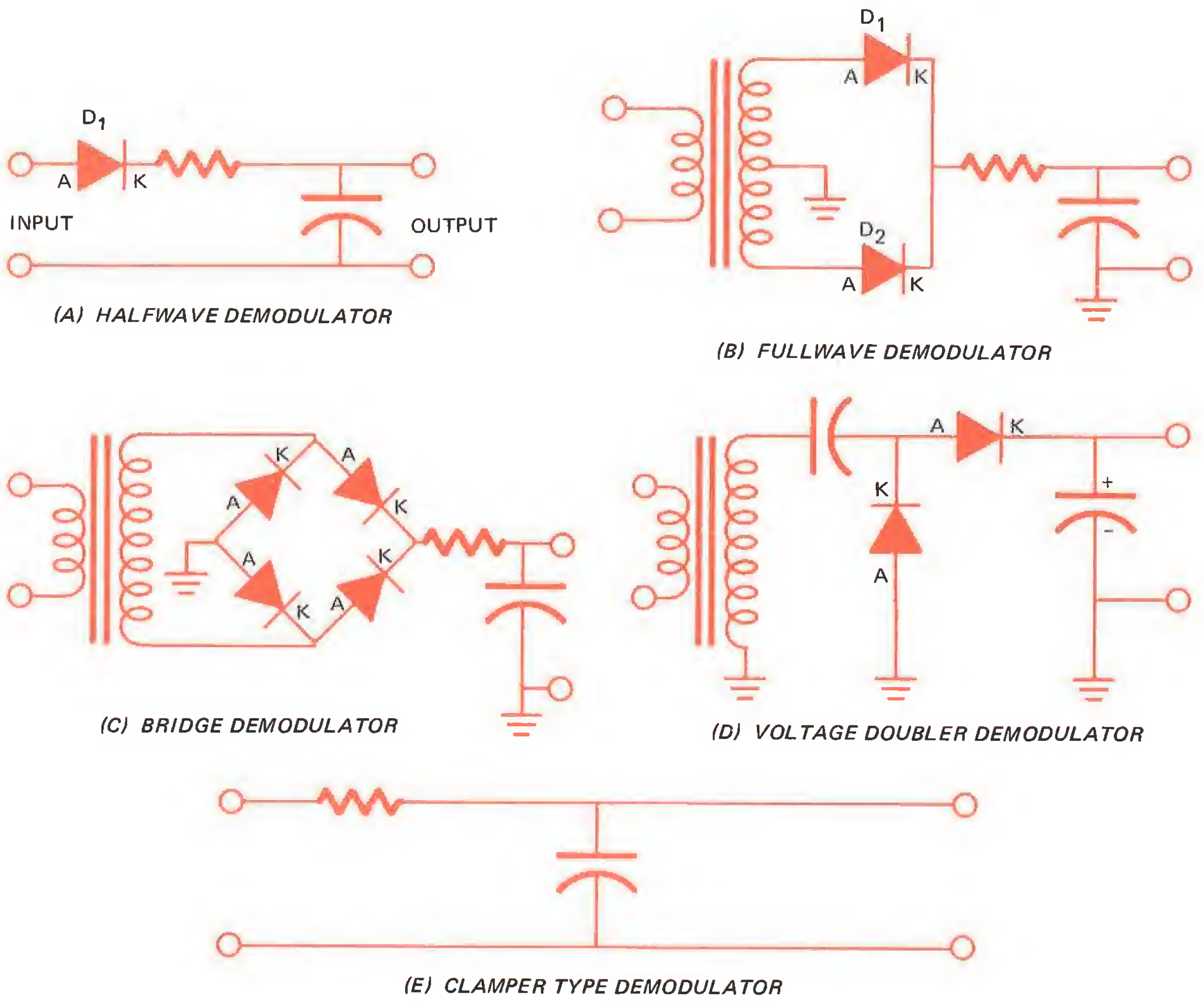


Fig. 27-7 Electronic Demodulators

The demodulator section in this system could be any one of those shown in figure 27-7, or, in fact, any other type of electronic rectifier circuit. The time constant of the filter circuit is normally selected to be long compared to the period of the chopper excitation signal *and* short compared to the period of any anticipated changes in the DC input signal. Moreover, since the output polarity is always the same, only one polarity of input signal can be accommodated.

Electromechanical demodulators are also used in many practical applications. Figure 27-8 shows two of the most commonly employed circuits. Their principal advantage is that the output can follow reversals in input polarity.

To understand how the electromechanical systems work, let's assume that the amplifier output is *exactly* out of phase with its input (much engineering effort goes into assuring that this is a reasonable assumption). Moreover, let's assume that we are dealing with truly rectangular waveforms. Figure 27-9 shows representation of the input and output under these conditions.

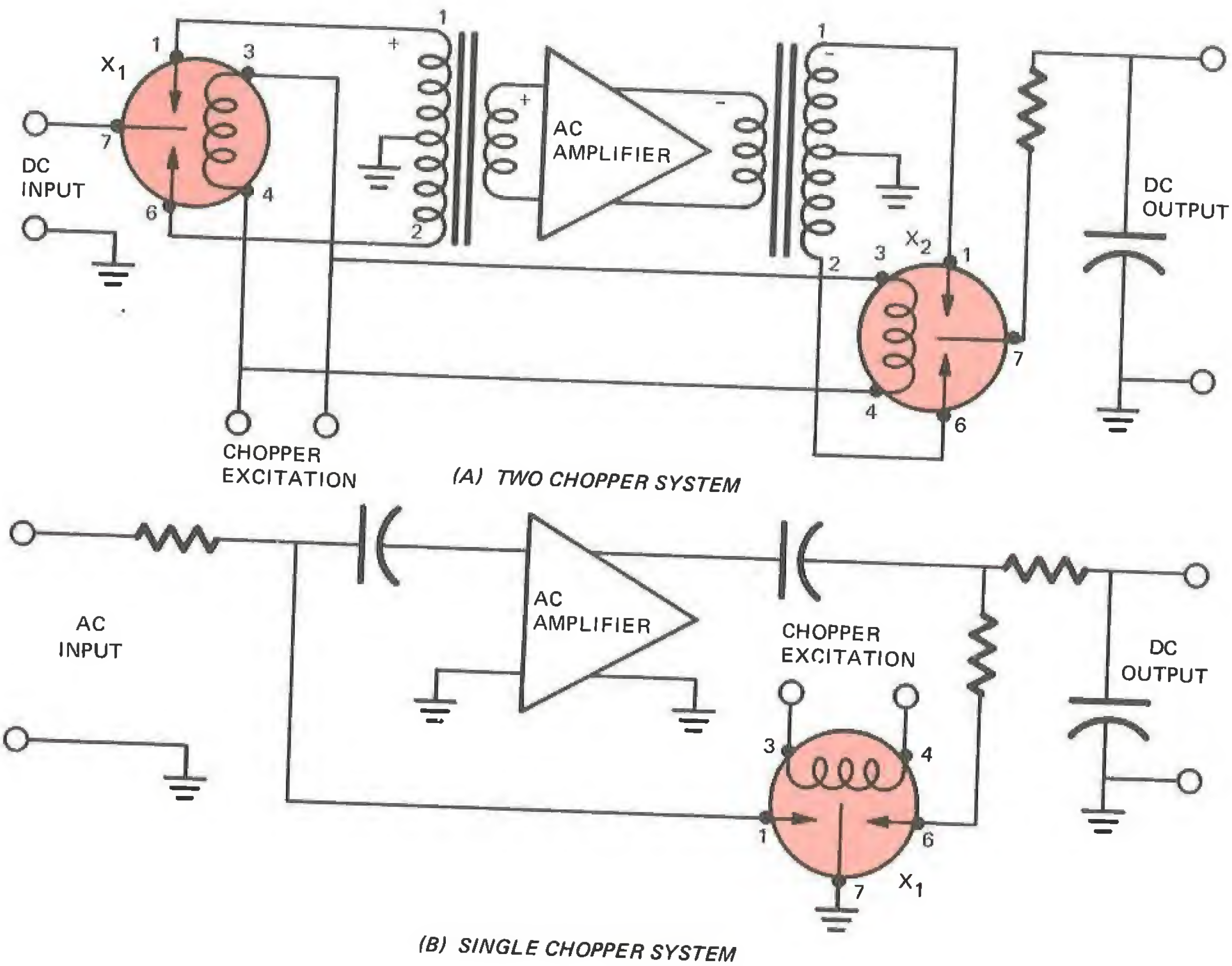


Fig. 27-8 Electromechanical Modulating-Demodulating Systems

Now, let's keep in mind that a typical electromechanical chopper is a *synchronous* device, that is, it vibrates in a fixed relationship to its excitation signal. So we can connect choppers X_1 and X_2 in figure 27-8a so that they both connect the armature to transformer (input and output, respectively) terminal 1 at the same time. So, assuming that the DC input voltage is positive and similar transformer polarities, when input terminal 1 is positive, output terminal 1 will be negative. Also, when input terminal 2 is positive, output terminal 2 is negative (remember that the two choppers *are* synchronized). As an overall result we can sketch the circuit waveforms shown in figure 27-10.

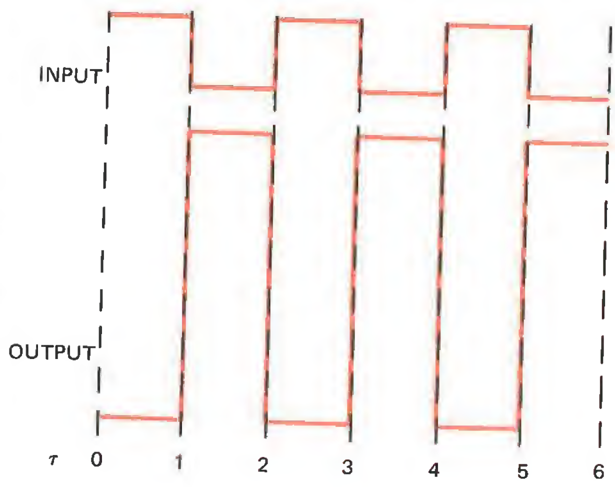


Fig. 27-9 Input and Output in an Electromechanical System

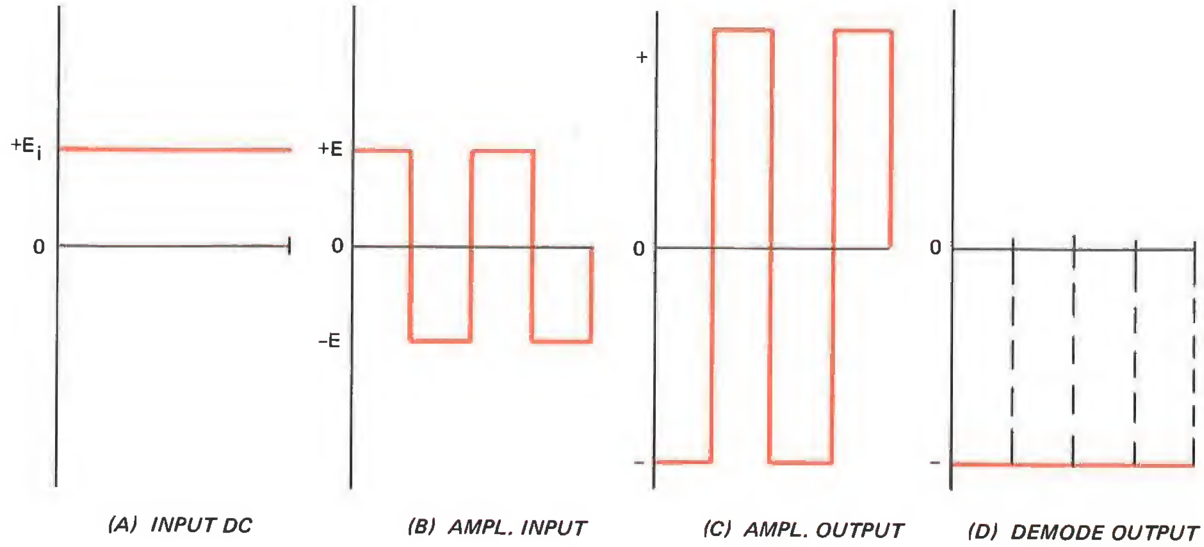


Fig. 27-10 System Signals

In other words, we have a +DC input and a -DC output. The system in figure 27-8a is effectively modulating, amplifying and demodulating the input signal.

Figure 27-8(b) is very much the same type of system except that the input and output are *grounded* on *alternate* half cycles. As a result, the polarity of the demodulated output is reversed as shown in figure 27-11.

Electromechanical choppers are also used in a variety of feedback systems employing additional windings on the input and output transformers. Moreover, they are used in systems which *stabilize* the characteristics of DC amplifiers. We shall not deal with these more complicated types of chopper applications here. However, you may wish to look up "chopper stabilization" in a text book on amplifier circuits for your own information.

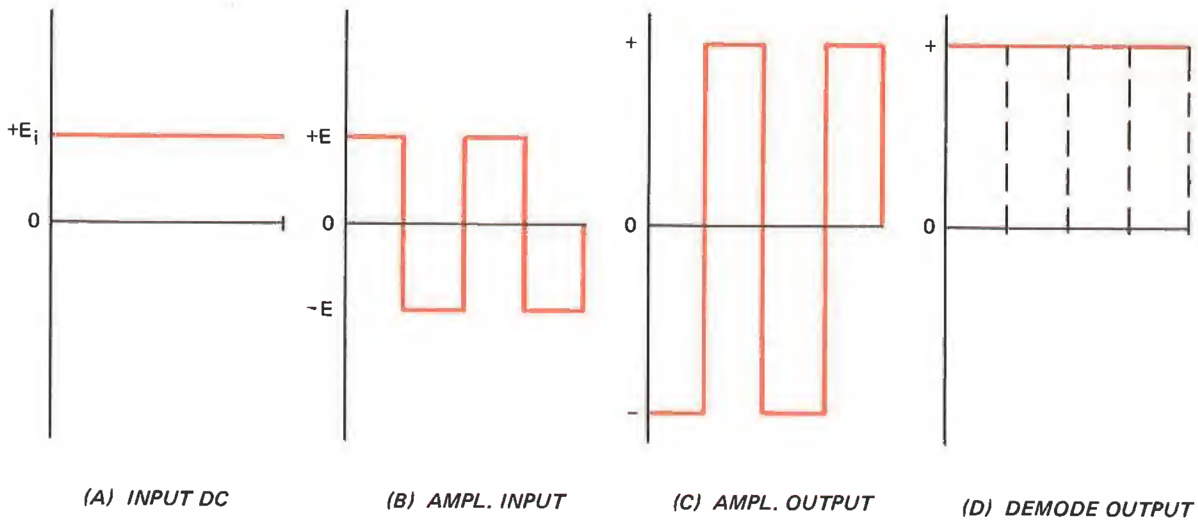


Fig. 27-11 Signals in a Single Chopper System

MATERIALS

1 Circuit board
2 Transistors (type 2N1304 or equivalent)
1 DC power supply (0 – 40V)
5 Diodes (type 1N270 or equivalent)
2 Resistors 10Ω 2W
1 Power transformer (1:1 ct)
1 Transistor input transformer (200Ω – 100Ω ct 1/2W)
1 Resistor 470Ω 1/2W
2 Resistors 560Ω 1/2W
2 Resistors 3.3k 1/2W
1 Resistor 4.7k 1/2W
2 Resistors 6.8k 1/2W
2 Resistors 47k 1/2W
3 Capacitors 10 μF 50W VDC
2 Capacitors 100 μF 25W VDC
1 Resistor 220Ω 2W
1 Resistance substitution box (15 – 10 megohm 1/2W)
1 VOM or FEM
1 Oscilloscope
1 Variable transformer (0 – 130V AC)
3 Sheets of linear graph paper

PROCEDURE

1. Construct the amplifier system shown in figure 27-12 (see page 202).
2. Construct the power supply divider network shown in figure 27-13; set the substitution box for maximum resistance.

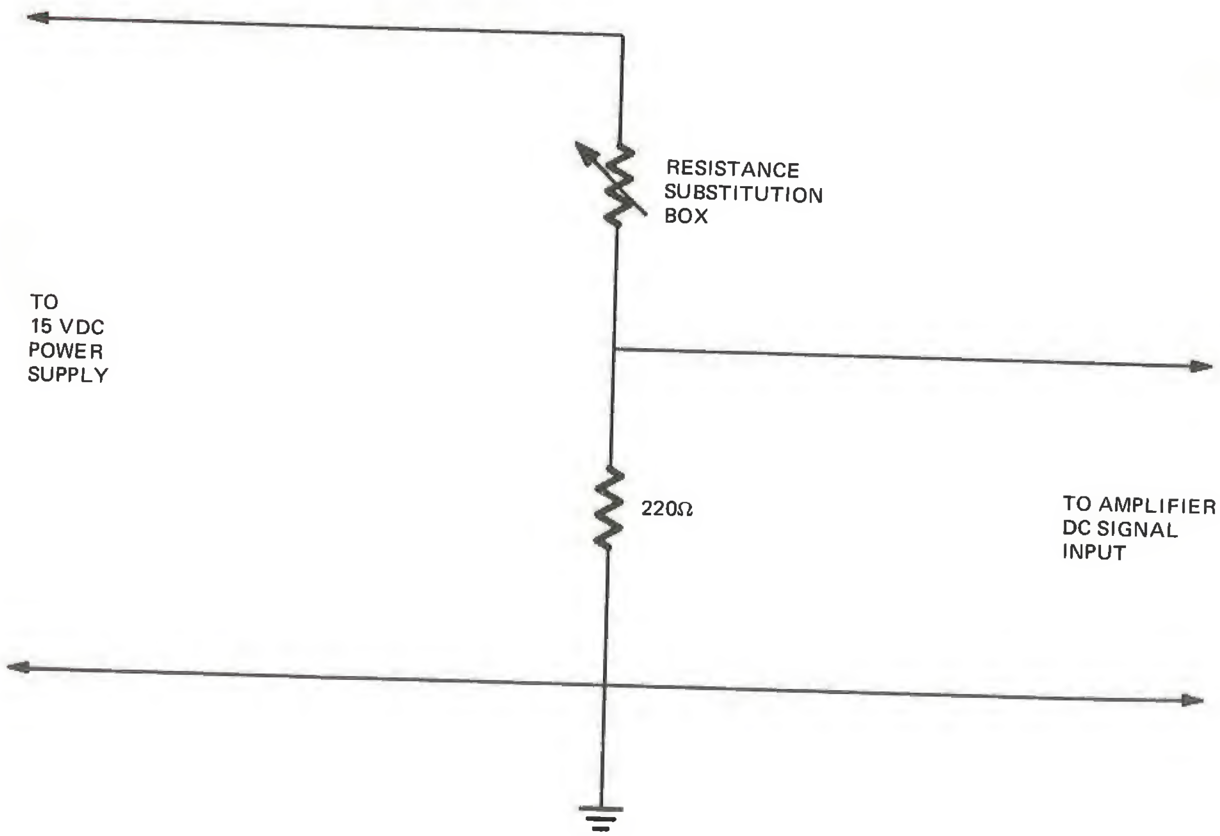
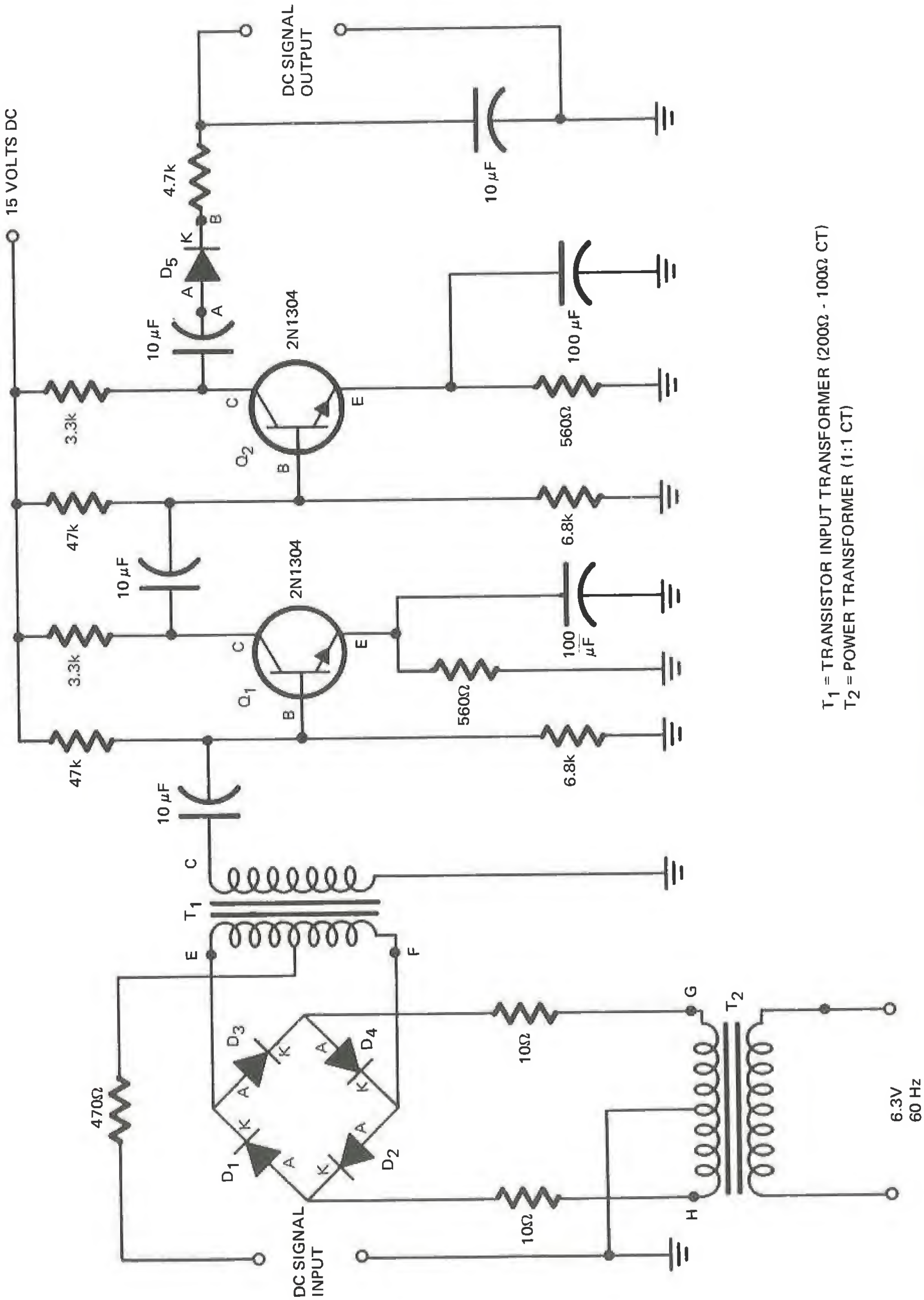


Fig. 27-13 Power Supply Divider Network



T_1 = TRANSISTOR INPUT TRANSFORMER (200Ω - 100Ω CT)
T_2 = POWER TRANSFORMER (1:1 CT)

Fig. 27-12 The Experimental Amplifier

3. Connect the power supply divider network to the amplifier input.

4. Connect a 6.3 VAC 60 Hz chopper excitation to the amplifier using the variable transformer. **Do not connect the AC until you are very sure it is 6.3 VAC.**

5. Connect the oscilloscope between ground and point A. Point A is the amplifier output before demodulation.

6. Decrease the resistance substitution box setting step-by-step until you see a signal at the oscilloscope. Continue decreasing the resistance substitution box setting while carefully watching the output waveshape. When you notice the output just beginning to distort, *increase* the substitution box setting one step.

7. Externally sync the oscilloscope on the undemodulated output signal. **Have your instructor check your circuit to insure that the scope is properly synchronized.**

8. Measure and record the DC level at point A (E_A).

9. On graph paper sketch the waveform showing its starting point, relative phase, amplitude, period, and DC level.

10. Move the vertical input of the scope to point B on the other side of D_5. Keep the scope externally synchronized on point A.

11. Repeat steps 8 and 9.

12. Move the vertical input of the scope to the output terminal of the system. Repeat steps 8 and 9 (external sync on point A).

13. Make these same measurements and sketches at:
    Point C located at the secondary of T_1.
    Point E located at the primary of T_1.
    Point F located at the primary of T_1.
    Point G located at the secondary of T_2.
    Point H located at the secondary of T_2.
    The DC signal input (E_i).

E_A	E_B	E_O	E_C	E_E	E_F	E_G	E_H	E_i

Fig. 27-14 The Data Table

ANALYSIS GUIDE. Using your waveform sketches, discuss the operation of the system. Give particular attention to the DC levels and time relationships of the various signals. Also discuss the overall DC-to-DC amplifier effectiveness.

PROBLEMS

1. How would you define the DC-to-DC *gain* of the amplifier in the experiment?
2. What was the value of the DC-to-DC gain for your amplifier?
3. What was the AC gain from point C to point A in your amplifier?
4. What was the AC gain from point C to point B in your amplifier?
5. Why are the three values of gain from problems 2, 3, and 4 different?

experiment 28 SINGLE-END POWER AMPLIFIERS

INTRODUCTION. The basic application of an electronic amplifying system is to take an input signal from a source and deliver it appropriately amplified to a load. In every case the amplifier output must satisfy the load's *power* requirements. In this experiment, we shall examine amplifier circuits expressly intended to deliver power to a load.

DISCUSSION. Electronic *power amplifiers* are built in a number of different circuit configurations. In this experiment we shall consider only one type of circuit, the single-ended transformer-coupled amplifier. Such amplifiers are typically found in the output stage of *audio frequency* equipment.

The basic power amplifier problem is to deliver the maximum undistorted power to a load. The circuit shown in figure 28-1 is one of the most frequently encountered arrangements.

In analyzing a power amplifier of this type the procedure is substantially the same as for other common emitter circuits. First, the Q-point is located by laying out the DC loadline and the bias line. It should be noted that the DC resistance of the transformer primary often constitutes an important part of the collector circuit resistance. Therefore, the DC loadline is drawn from V_{CC} on the collector-emitter voltage axis of the transistor output characteristic to

$$I = \frac{V_{CC}}{R_E + R_C}$$

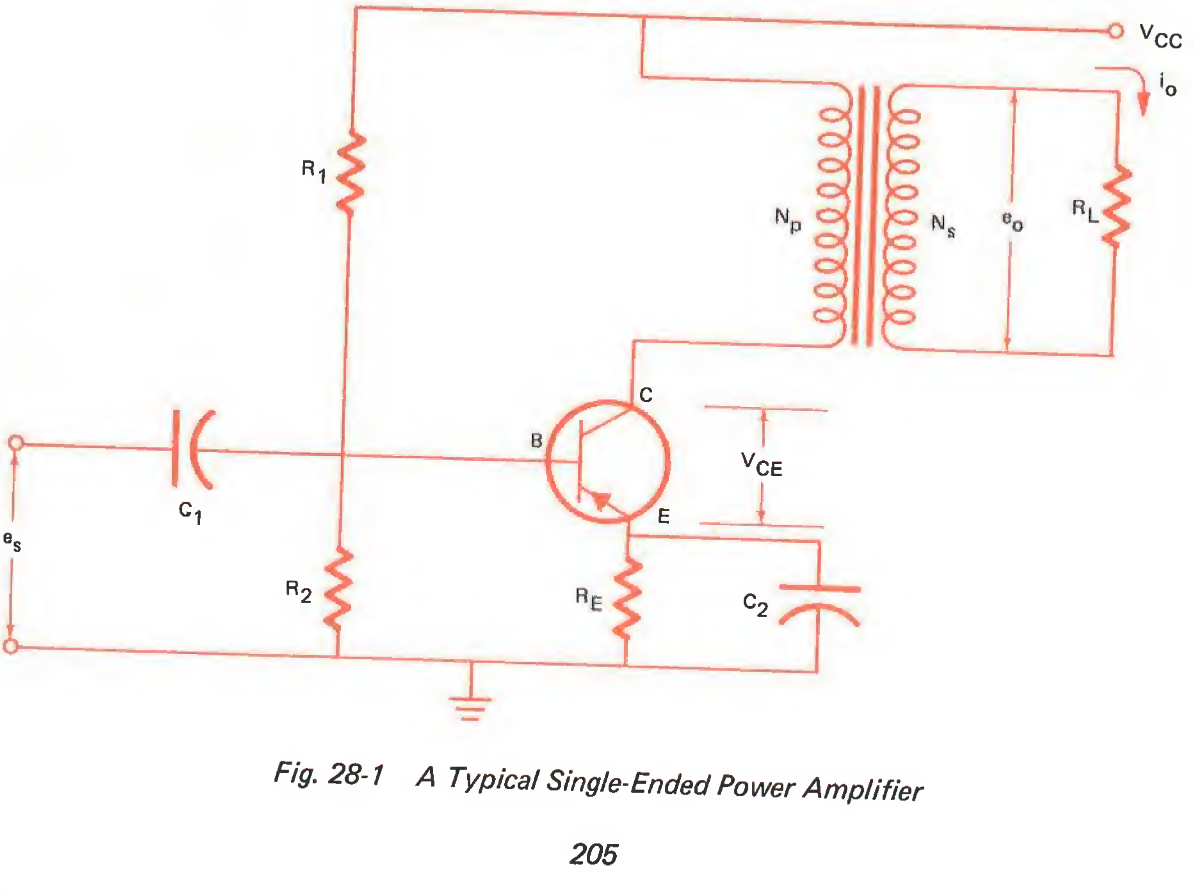


Fig. 28-1 A Typical Single-Ended Power Amplifier

On the collector current axis, R_C is, of course, the DC resistance of the transformer primary winding.

The bias line is plotted in the usual way employing the equation

$$V_{CE} = I_B\left[\frac{(R_L + R_E)(R_B + R_E)}{R_E} - R_E\right] + \left[V_{CC} - \frac{(R_L + R_E)(V_{BB} - V_{BE})}{R_E}\right] \quad (28.1)$$

where

$$R_B = \frac{R_1 R_2}{R_1 + R_2},\ V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2} \text{ and,}$$

V_{BE} is approximated at 0.2 volts for germanium transistors or 0.6 volts for silicon devices.

Since one of the objectives of a power amplifier is to deliver maximum power to the load, it follows that the input power should be as large as the active device (transistor, in this case) can accommodate. The maximum average power that can be applied to a transistor (or other device) is limited by the heat-dissipating ability of the device. The heat-dissipation rating of a particular device is normally specified by the manufacturer in watts.

We can plot the *power dissipation* of a device on the output characteristic curves using the equation

$$P = V_{CE}I_C \quad (28.2)$$

For example, let us suppose that a power transistor is rated at 5 watts when operated in free air. For this device the collector current cannot exceed 1 amp when the collector voltage is 5 volts ($P = 5 \times 1 = 5W$). Similarly the current may not exceed 0.5 amps when the voltage is 10 volts. Proceeding in this way we can tabulate pairs of current, voltage values which satisfy the relationship

$$V_{CE}I_C = 5 \text{ watts}$$

and the results will be

V_{CE}	5 volts	10 volts	15 volts	20 volts
I_C	1.0 amp	0.5 amps	0.33 amps	0.25 amps

If we plot these points on the (utput characteristic, the curve will appear as shown by the dotted color line in figure 28-2. The DC loadline and bias line are also shown in figure 28-2 (as is the AC loadline).

A few moments of reflection will confirm that if the Q-point lies above the 5 watt maximum dissipation line, then the transistor will get too hot. On the other hand, if the Q-point is far below the 5W maximum dissipation line, then the output signal power will be unnecessarily limited. As a result it is common practice to locate the Q-point near, but well beneath, the maximum dissipation line.

With the Q-point established, the AC loadline may be drawn. The AC load on the transistor (R_p) is the resistance reflected into the transformer primary by the secondary load (R_L).

If we assume that the transformer losses are negligible, then the AC primary and

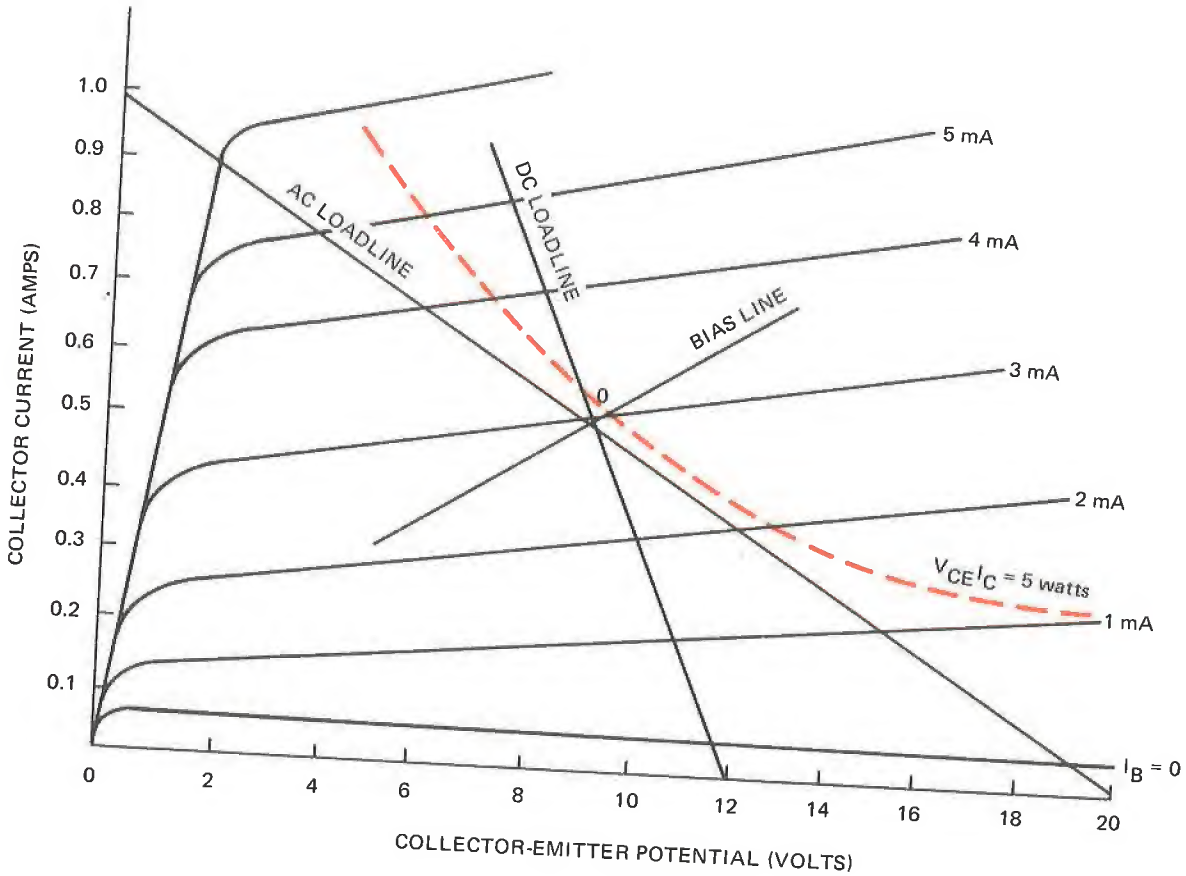


Fig. 28-2 Graphical Analysis of a Power Amplifier

secondary powers are equal:

$$P_C = P_o$$

The output AC power is given by

$$P_o = E_o I_o$$

while the primary AC power is

$$P_C = V_{CE} I_C$$

Consequently we have

$$V_{CE} I_C = E_o I_o$$

We can apply Ohm's law to the primary and secondary circuit and observe that

$$I_C = \frac{V_{CE}}{R_p} \text{ and } I_o = \frac{E_o}{R_L}$$

where R_p is the *effective* AC load resistance on the transistor.

Substituting these current relationships into the above equation, we have

$$\frac{V_{CE}^2}{R_p} = \frac{E_o^2}{R_L}$$

or

$$R_p = R_L \left(\frac{V_{CE}}{E_o}\right)^2$$

And we recognize the ratio V_{CE}/E_o as being equal to the turns ratio N_p/N_s of the transformer. We may therefore write

$$R_p = R_L\left(\frac{N_p}{N_s}\right)^2 \qquad \textbf{(28.3)}$$

as the value of the AC load resistance of the stage and this is the value that we use to draw the AC loadline.

Since the signals handled by power amplifiers are typically very large, the gain is normally determined graphically. Small signal analysis is not used for power amplifier stages. Let us consider the amplifier represented by the curves given in figure 28-3. If the Q-point is located midway between E_{max} and E_{min} as well as midway between I_{max} and I_{min}, then the peak collector voltage and current swing will be

$$V_{CE(peak)} = E_Q - E_{min}$$

and

$$i_{C(peak)} = I_Q - I_{min}$$

For most practical transistors, I_{min} will be so small compared to I_Q that it may be neglected and we may write

$$I_{C(peak)} \approx I_Q$$

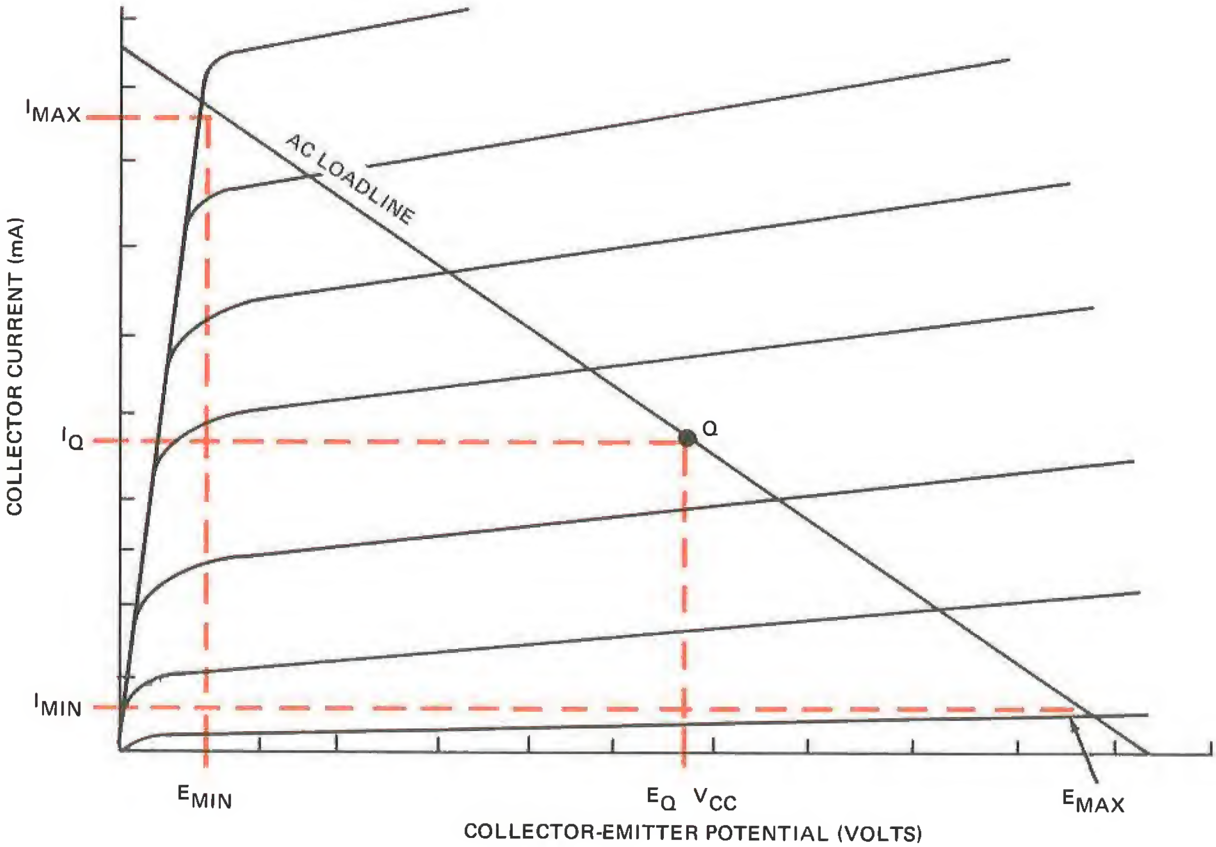


Fig. 28-3 Analysis of Output Power

Therefore, the rms collector current will be

$$\boxed{I_{C(rms)} \approx \frac{I_Q}{2}} \qquad (28.4)$$

And since the rms voltage across R_p is

$$V_{CE(rms)} = I_{C(rms)} R_p$$

and the output power is given by

$$P_o = V_{CE(rms)} I_{C(rms)}$$

we may write the following equation for output power:

$$P_o = I_C{}^2(rms)\, R_p$$

or

$$P_o \approx \frac{I_Q{}^2}{2} R_p \qquad (28.5)$$

And finally in terms of the turns ratio and R_L we have

$$P_o \approx 1/2(I_Q \frac{N_p}{N_s})^2 R_L \qquad (28.6)$$

We should remember that this is the *maximum power output* that we can expect if the transistor is biased in the center of the usable portion of the loadline. Moreover, the equation above (28.6) presumes a perfect transformer. Actually, it is much more reasonable to assume a transformer efficiency of about 75%. If this is done, equation 28.6 becomes

$$P_o \approx 3/8(I_Q \frac{N_p}{N_s})^2 R_L$$

The input power to the amplifier stage will be

$$P_{in} \simeq I_{in}{}^2(rms) R_{in}$$

And the power gain (K_p) becomes

$$K_p = \frac{P_o}{P_{in}} \qquad (28.7)$$

and is usually expressed in decibels.

MATERIALS

1 Power transistor (type T13027 or equivalent)
1 Output characteristic for the above transistor
1 Output transformer
1 4 ohm load resistor 1W
1 15 ohm 2 watt resistor
2 10k ohm resistors 1/2W
1 100 µF 50W VDC capacitor
1 10 µF 50W VDC capacitor
1 Variable DC power supply (0-40V)
1 VOM or FEM
1 Audio generator
1 Oscilloscope

PROCEDURE

1. Determine the primary resistance R_C and turns ratio (N_p/N_s between the primary and 4Ω secondary) of the output transformer.
2. On the transistor output characteristic, plot the DC loadline and the bias line for the circuit shown in figure 28-4.

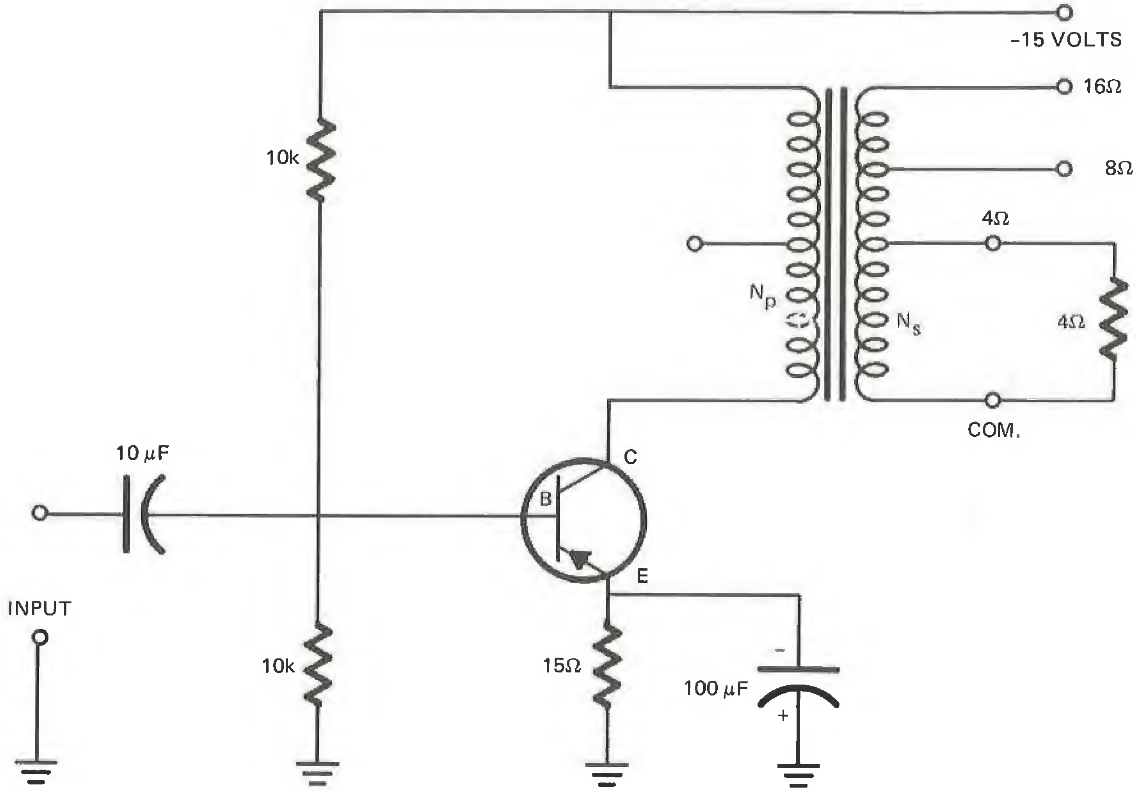


Fig. 28-4 The Experimental Circuit

3. Locate and record the Q-point values of E_Q and I_Q from the curve.
4. Plot the maximum power dissipation curve for a free-air dissipation of 2 watts. Determine whether or not the transistor is operating in the proper region.
5. Assemble the circuit shown in figure 28-4 and measure the values of E_Q and I_Q.
6. Connect the audio generator to supply an input at 1 kHz. Connect the oscilloscope across the 4-ohm load resistor. Adjust the audio level for the largest input signal that produces a relatively undistorted output waveform.
7. Record the levels of both the output and input signals [$E_{o(rms)}$ and $E_{in(rms)}$].
8. Determine the input resistance of the amplifier (R_{in}).
9. Using $P_o = \dfrac{E_o{}^2\,(rms)}{R_L}$ and $P_{in} = \dfrac{E_{in}{}^2\,(rms)}{R_{in}}$ determine both the input and output power levels. Record these values as measured quantities.
10. With the appropriate equation from the discussion, compute the approximate value of P_o using circuit component and output characteristic quantities.
11. Using the measured values of P_o and P_{in}, compute the power gain of the stage in decibels.

Qty	R_C	N_p/N_s	E_Q	I_Q	E_o (rms)	E_{in} (rms)	R_{in}	P_o	P_{in}	K_P (db)
Measured Values										
Computed Values										

Fig. 28-5 The Data Table

ANALYSIS GUIDE. The objective of this experiment has been to examine the operation of a single-ended power amplifier. In analyzing your results you should concentrate on evaluating the effectiveness of the circuit in delivering audio power to the load. You should also consider how accurately the equations given predicted the actual power delivered to the load.

PROBLEMS

1. Approximately what turns ratio would be required to deliver 1.0 watts to a 10-ohm load if the other circuit values were as given in figure 28-4?
2. Explain in your own words how it is possible to have a peak-to-peak voltage between collector and emitter which is greater than V_{CE}.
3. If the *circuit efficiency* of a power amplifier is defined as

$$\% \text{ eff} = \frac{\text{output signal power}}{\text{dc power input}} \times 100$$

what was the percent efficiency of the circuit in the experiment?

experiment 29 PUSH-PULL POWER AMPLIFIERS

INTRODUCTION. Single-ended *power amplifiers* require relatively large values of quiescent current with the result that considerable heat must be dissipated even when no signal is present. One way to avoid this large no-signal power dissipation is to use a class B push-pull power amplifier. In this experiment we shall examine the operation of such a circuit.

DISCUSSION. Let us consider the amplifier circuit shown in figure 29-1. The circuit operation can be explained as follows: Both transistors have zero base bias current, and, being PNP types, respond only to negative base signals. When no input signal is applied, both transistors are operating at cutoff and, therefore, have very small collector currents. Figure 29-2 shows the output characteristic of a transistor operating in this manner.

If we apply a sinusoidal input to the primary of the input transformer and the instantaneous polarities marked in figure 29-1, then transistor T_2 experiences a positive input current and is driven further into cut off. Transistor T_1, on the other hand, experiences a negative input which is amplified and coupled to the load through the lower half (N_{p1}) of the output transformer primary. Consequently, we see that during the half of the input cycle marked No. 1, the load is supplied with power by transistor T_1 while T_2 remains cut off.

During the alternate half cycle (No. 2), T_1 experiences a positive input and remains cut off while T_2 experiences a negative input which is amplified and delivered to the load through the upper half (N_{p2}) of the output transformer primary.

We may plot the AC loadline for each transistor by observing that the load is reflected into the output transformer primary

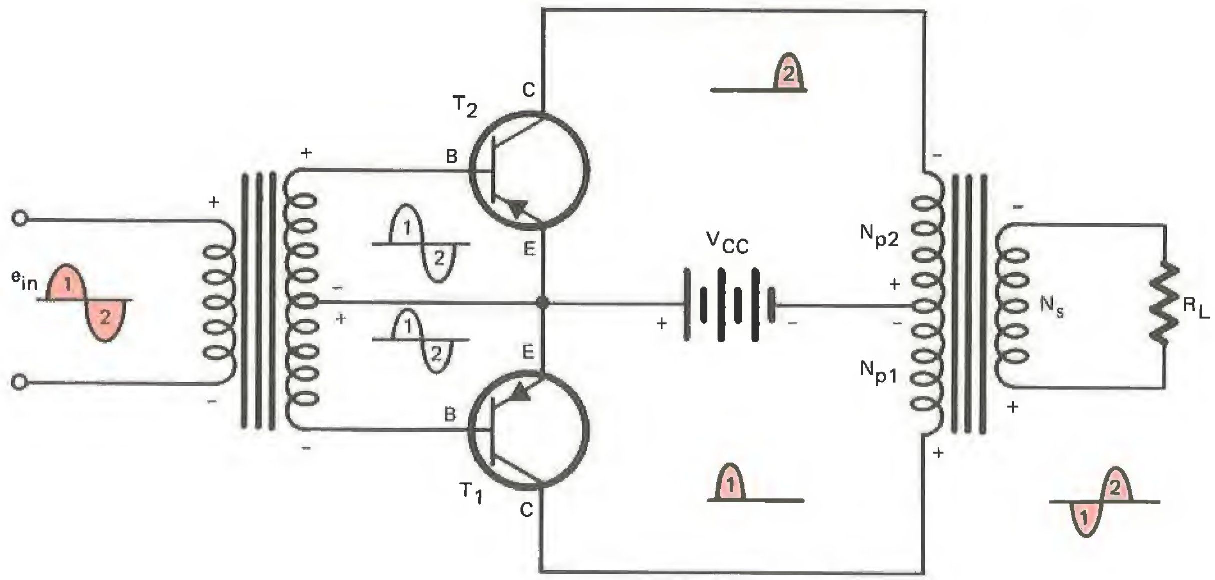


Fig. 29-1 A Basic Push-Pull Amplifier Circuit

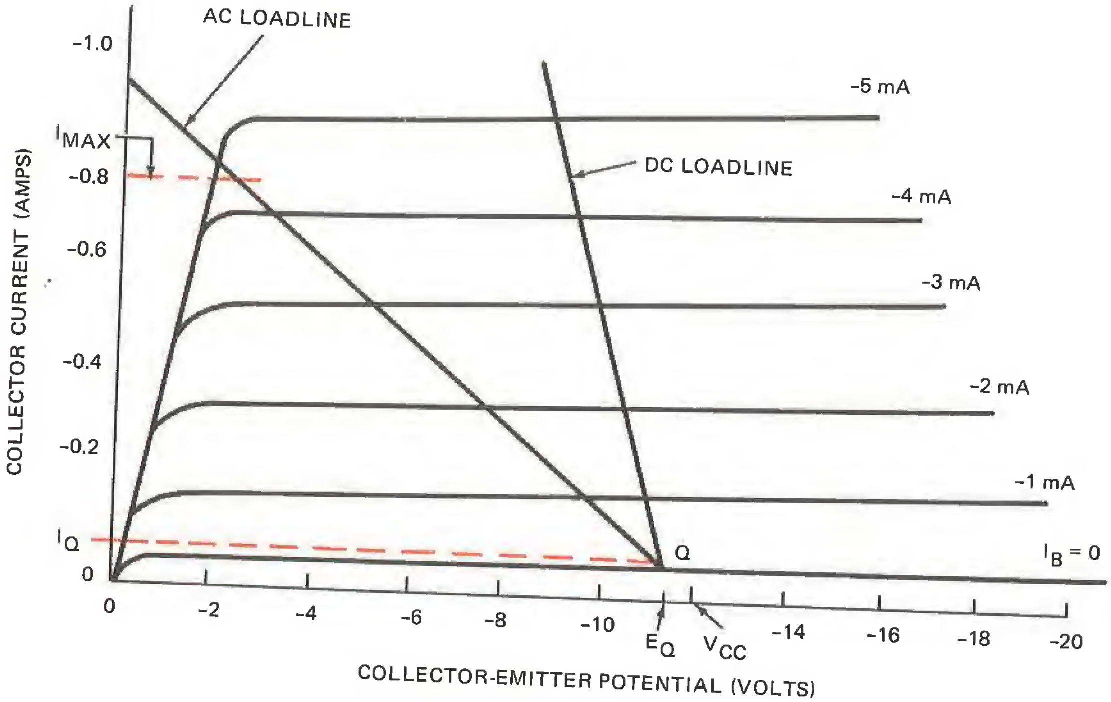


Fig. 29-2 Loadline Plots for Zero Bias

according to

$$R_p = R_L\left(\frac{N_{p1}}{N_s}\right)^2 = R_L\left(\frac{N_{p2}}{N_s}\right)^2 \qquad \textbf{(29.1)}$$

Each transistor can accommodate a peak collector current swing along the AC loadline of

$$i_{C(peak)} = I_{max} - I_Q$$

And since I_Q is normally very small compared to I_{max}, we may approximate the peak collector current swing by

$$i_{C(peak)} \simeq I_{max}$$

When this approximation is valid, the rms collector current will be

$$I_{rms} \approx \frac{I_{max}}{\sqrt{2}}$$

And the power delivered to the output transformer primary becomes

$$P_p = (I_{rms})^2 \; R_p$$

Finally, if the output transformer has a typical efficiency of around 75 percent, the output power is

$$P_o \approx 3/8 \left(I_{max}\frac{N_p}{N_s}\right)^2 R_L \qquad \textbf{(29.2)}$$

In the input circuit, the transformer serves to couple the power amplifier to any preceding stage, as an impedance matching device and as a phase splitter, to supply the two bases with signals that are 180° apart.

While the circuit shown in figure 29-1 is practical in the sense that it will work, one major problem grows out of the fact that the input characteristics of the transistors are

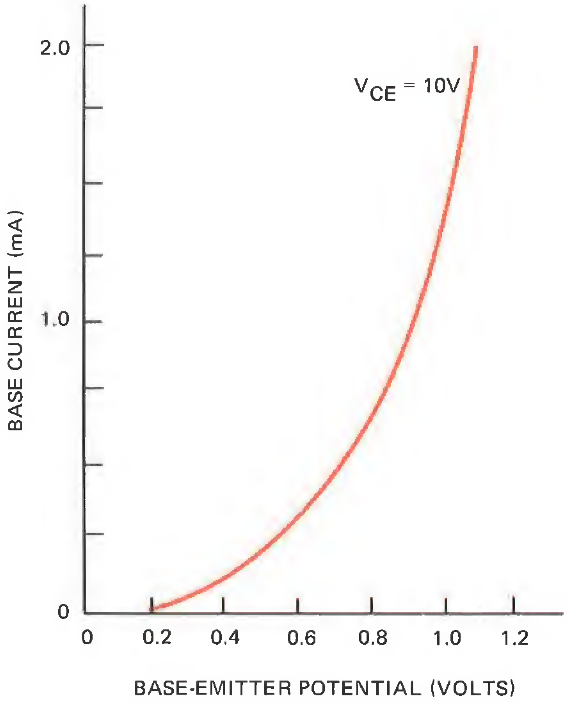


Fig. 29-3 A Typical Silicon Transistor Input Characteristic

quite nonlinear. Figure 29-3 shows a typical silicon transistor input curve. Notice that the input curve is relatively linear for base currents above about 0.25 mA, but is quite nonlinear between zero and 0.25 mA. If we bias the two push-pull transistors at zero base current, then some distortion of the output will result. This type of distortion is called *crossover distortion* and may be avoided by biasing both transistors slightly above the nonlinear portion of the input curve. Figure 29-4 shows a push-pull amplifier circuit in which bias has been provided for this purpose.

In this circuit R_1 and R_2 are the usual base bias resistors. The emitter resistors, R_E, are included to improve the bias stability and also to contribute slightly to gain stability.

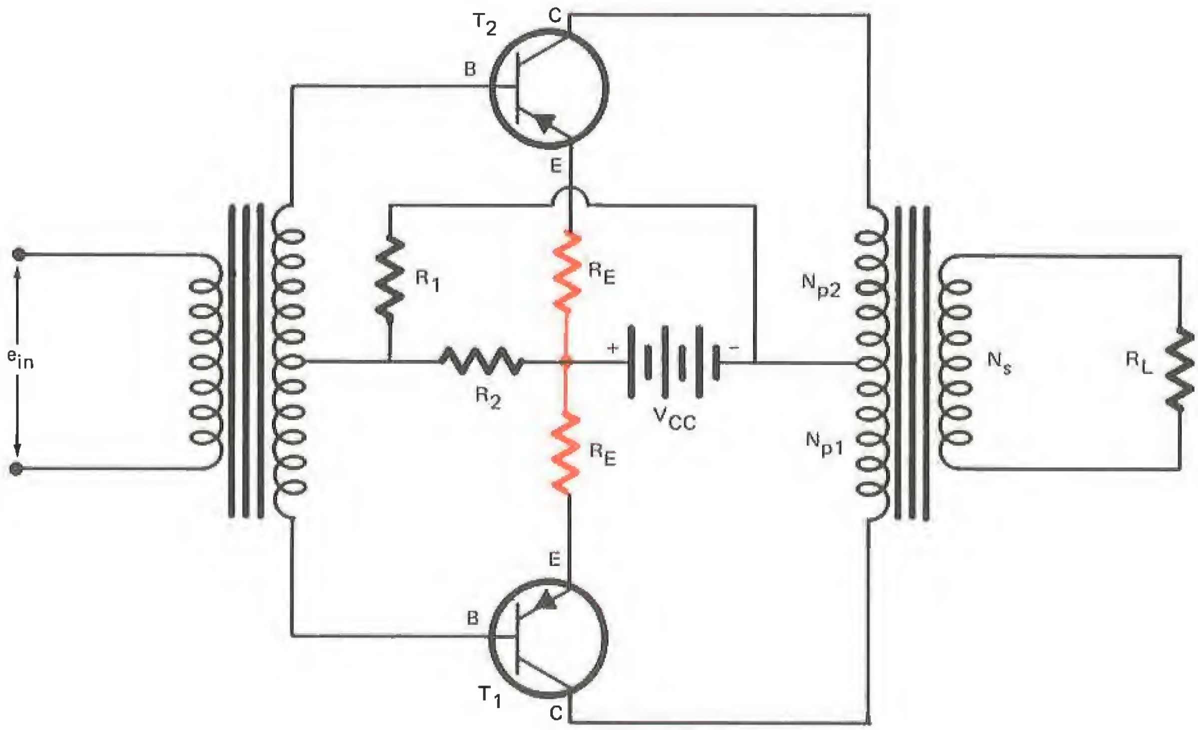


Fig. 29-4 Biasing Against Crossover Distortion

MATERIALS

2 Power transistors, type TI 3027 or equivalent
1 Output characteristic for the above device
1 Output transformer (100Ω CT - 16/8/4Ω 5W)
1 Input transformer (500Ω CT - 200Ω CT 1/2W)
1 4-ohm resistor 2W
2 0.47-ohm resistor 2W
1 470-ohm resistor 1/2W
1 15k resistor 1/2W
1 Oscilloscope
1 VOM or FEM
1 Variable DC power supply (0 - 40V)
1 Sheet of linear graph paper
1 Resistance substitution box (15-10 megohm 1/2W)
1 Audio generator
1 0.01 μF capacitor 600W VDC

PROCEDURE

1. Measure and record the DC resistance (R_C) between one end of the output transformer primary and the center tap.
2. Determine the turns ratio between one half of the output transformer primary and the 4-ohm secondary.
3. Assemble the circuit shown in figure 29-5.
4. Measure and record the DC collector current and the collector-emitter voltage.
5. Using the values from step 4, plot the Q-point on the output characteristic.
6. Using the value of R_L and the turns ratio, determine the effective AC load resistance (R_p).

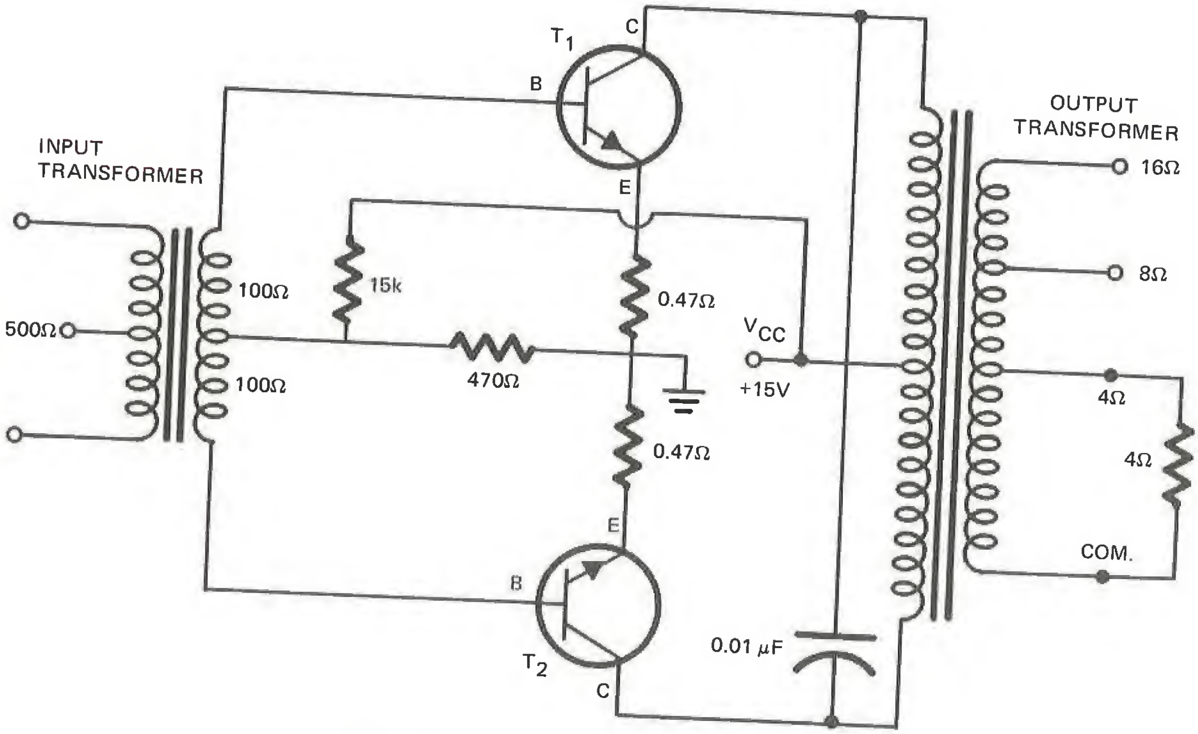


Fig. 29-5 The Experimental Amplifier

7. Plot the AC loadline on the output characteristic. From your plot determine the value of I_{max}.
8. Compute and record the output power using equation 29.2.
9. Connect the audio generator to the input and adjust it for the maximum undistorted 1 kHz signal across the 4-ohm load. Record the value of e_o.
10. Compute the output power, $P_o = E_L{}^2/R_L$.
11. With the oscilloscope view the waveform:
    (a) at the input terminals.
    (b) across each half of the input transformer secondary.
    (c) across each half of the output transformer primary.
    (d) across the load resistor.

    Make an accurate sketch of each waveform on linear graph paper.
12. Insert the resistance substitùtion box in series with the audio generator and connect a meter across the box.
13. Adjust both the resistance box setting and the audio generator such that you have the same value of e_o as before *and* a readable voltage on the meter.
14. With the meter reading and resistance box value, compute the input power (P_i).
15. Compute the power gain, $K_p = P_o/P_i$.

Qty	R_C	$\frac{N_p}{N_s}$	I_C	V_{CE}	R_p	I_{max}	P_o comp.	e_o	P_o meas.	P_i meas.	K_p
Value											

Fig. 29-6 The Data Table

ANALYSIS GUIDE. In analyzing these data, you should consider the effectiveness of the experimental circuit as a power amplifier. Also consider how each of the waveforms viewed contributes to the overall performance of the amplifier.

PROBLEMS

1. Assuming that the same transformer is used, what would have been the output power if the load in the experiment was connected between the common tap and the 8-ohm tap of the output transformer?
2. Explain how the input resistance of the amplifier in figure 29-5 is related to the input resistance of one of the transistors.
3. Explain *crossover distortion* in your own words, and tell how *each* of the waveforms viewed in the experiment would have been affected by this type of distortion.

experiment 30 AMPLIFIER TROUBLESHOOTING

INTRODUCTION. Electronic amplifiers will occasionally fail to perform properly. In this experiment we shall examine techniques that are appropriate for locating the causes of common types of amplifier trouble.

DISCUSSION. Amplifier failures may be divided into a number of major categories. The following major divisions will include the vast majority of troubles:

1. *An amplifier with a normal input signal may have no output at all.*
2. *An amplifier with a normal input may have seriously reduced output.*
3. *An amplifier with a normal input may produce a distorted output.*
4. *An amplifier may oscillate at some frequency.*
5. *An amplifier's output may contain objectional amounts of noise or hum.*

Each of these five types of trouble is discussed individually in the following paragraphs.

Before discussing individual trouble categories, it is worthwhile to recognize that, in a laboratory situation, two additional types of trouble can arise. They are; (a) errors in circuit wiring, and (b) errors in circuit design. The first of these can usually be corrected quickly by carefully checking the circuit against the original diagram and examining each connection.

The second type of error is much more difficult to correct. The usual process is to perform a detailed analysis of all the operating potentials (normally done graphically) and small signal performance.

If we are sure that neither of the two types of errors mentioned above are occurring, then we may proceed in dealing with the five troubles outlined originally.

In troubleshooting an amplifier (or other electronic system), we normally make two basic assumptions upon which to proceed. The first is that the circuit was functional before the failure. (*This is the same as assuming that there is no error in circuitry or design.*) Secondly, we assume that there is only one problem to be located in the circuit. (*This does not exclude the possibility of several different failures, but does let us deal with one problem at a time.*) With these basic assumptions in mind, let us now proceed with each of the five types of troubles.

No Output Signal. If the input signal to an amplifier is normal and there is no output signal, then we can conclude that at some point in the signal path there is a component which has failed in such a way as to completely block signal flow. Our problem then is to locate this single defective component. To better understand the troubleshooting process, let us use the circuit shown in figure 30-1 as an example.

The first step in any troubleshooting process is to check the DC operating potentials. In the example circuit, we would measure the values of V_{CC} and V_{CE} of each transistor (in the case of an FET, we measure V_{DS}, while for a tube we measure E_{PK}, E_{G2}, and observe filament operation). Normally, in a class A amplifier, we expect V_{CE} (V_{DS} or E_{PK}) to be *approximately* 1/2 V_{CC} (V_{DD}

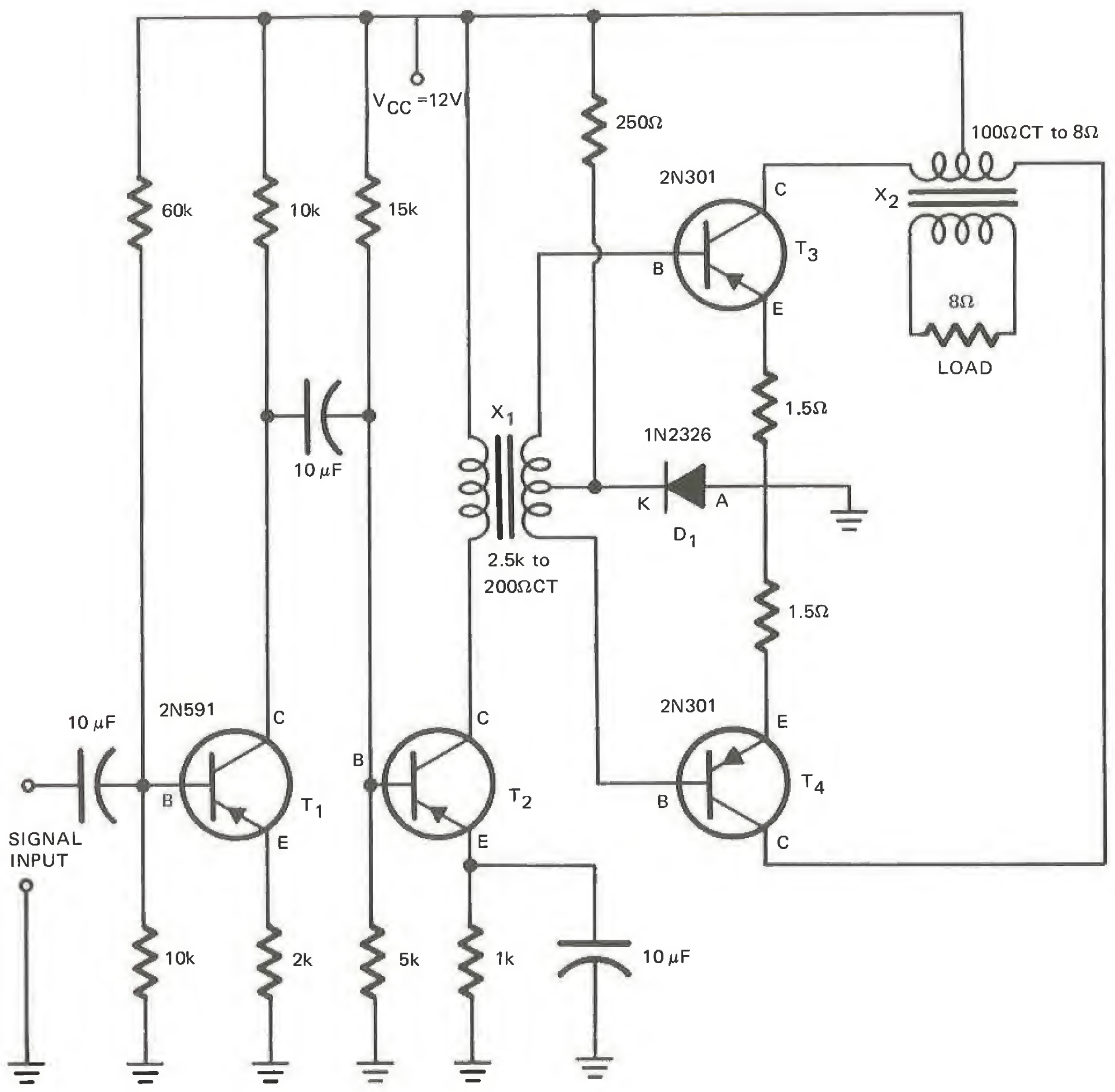


Fig. 30-1 A Typical Amplifier Circuit

or E_{BB}). A class B amplifier, on the other hand, usually has a V_{CE} (V_{DS} or E_{PK}) of *about* 9/10 V_{CC} (V_{DD} or E_{BB}).

As a result, we would expect V_{CE} to be about 6V for the first two transistors and about 10V for the two output transistors. If the V_{CE} value measured for one of the transistors was *greatly different* from the expected value, then we would *suspect* that stage of being defective.

After checking the operating potentials of the circuit, we should apply a normal signal to the input of the amplifier. We may then check the signal level (using an oscilloscope or other instrument) at various points within the circuit. By starting at the input and work-

ing toward the output, we can locate the point at which the signal becomes lost. In the example circuit, the signal should be checked at:

(a) the input terminals
(b) the base of T_1
(c) the collector of T_1
(d) the base of T_2
(e) the collector of T_2
(f) the base of T_3
(g) the collector of T_3
(h) the base of T_4
(i) the collector of T_4
(j) the output terminals

Notice that what we are doing here is checking the signal at the input and output of each device, proceeding from the input to the output of the amplifier. When the point is found at which no signal is present, then we can usually isolate the defective component by a careful examination of the circuit. For instance, suppose that the signal is present at the base of T_2 and not at the collector of T_2. This being the case, we conclude that the defect must be caused by transistor T_2, transformer X_1, or the resistor-capacitor network in the emitter circuit of T_1. We can check each of these components one at a time to find the fault. Moreover, the operating potentials measured at T_1 may help in locating the defect. If V_{CE} is equal to V_{CC}, then T_2 must be an open circuit. Or if V_{CE} is zero, then either T_2 is shorted or another device (X_1 or the emitter resistor) is open. Measuring the DC voltage across the emitter resistor will indicate whether or not current is flowing in the circuit. If current is flowing, then there can be no open-circuited component.

In this way we can locate any component which is causing the signal to be lost.

Reduced (or Weak) Output Signal. A seriously reduced output signal is usually caused by either a weak device (transistor with low h_{fe}, or low g_m in case of tubes and FETs) or by a defective coupling network. Checking the signal level at the input and output of each device will usually reveal the cause of the trouble. For instance, if the signal is normal at the collector of T_1 in the example circuit, and severely reduced at the base of T_2, then the coupling capacitor may have abnormally high reactance (low capacitance). This symptom could also be caused by a reduced input resistance (h_{ie}) for T_2. However, a change in h_{ie} will normally cause a serious change in DC operating potentials.

Transformers can fail causing a severe reduction (or even total loss) of signal. If one or more turns *of any winding becomes shorted, then the short circuit is reflected into all of the windings.* This trouble is difficult to identify and is usually the last possibility to be investigated. Perhaps the best way to test a transformer is to replace it with another known good one.

Distorted Output. Distortion in the output of an amplifier is most frequently caused by a shift in Q-point of one of the devices. Such a Q-point shift will normally be accompanied by a change in operating potentials. The two most common causes of distortion are: (a) defective devices (transistors, tubes, FETs) and (b) leaky coupling capacitors. The second of these (leaky capacitors) causes Q-point shift by allowing DC current to leak from the output (collector) of one device to the input (base) of another.

It should be noted that output of a push-pull class B amplifier becomes severely distorted if one of the devices fails.

Oscillation. Perhaps the most troublesome amplifier problem is spurious oscillation. Oscillation occurs when a portion of the output of one stage gets into a previous input circuit and supports the input signal. Oscillation is therefore the result of regenerative feedback. Accidental regenerative feedback can occur when:

(a) circuit wiring is carelessly done.

(b) circuit or component shielding is inadequate.

(c) some component has signals from several stages applied to it.

(d) the circuit gain has sharp peaks.

When undesirable oscillation occurs, the usual troubleshooting technique is to observe the oscillation with an oscilloscope while moving circuit components, wires, and shields. Any change in oscillation when a particular part is moved indicates that the part is *one* of the affected ones.

A fairly common cause of oscillation in an amplifier is inadequate power supply filtering. Such inadequate filtering allows signal current from all of the stages to flow through the power supply internal impedance, thereby providing a feedback path.

Faulty ground connections may also cause oscillation by providing a resistance that is common to several stages.

Noise and Hum. Noise is thermally-generated, randomly-distributed energy usually produced within electronic components (resistors, transistors, capacitors, etc.). Carbon resistors and transistors are perhaps the worst offenders and the usual troubleshooting process is to watch the output noise level with an oscilloscope while suspected components are tapped briskly with a pencil or other light object. When a noisy component is located, it is replaced with a known good one. Noise is the one trouble which is frequently caused by more than one defective component at a time.

Hum is low frequency noise and is almost always related, frequency-wise, to the 60-Hz AC line. Hum may get into an amplifier in one of four basic ways:

(a) The DC power source may be inadequately filtered allowing a hum signal to pass through into the amplifier.

(b) Ground loops (ground points which are at different AC levels) can induce hum into amplifier circuits.

(c) Any high impedance circuit can have hum induced into it by stray magnetic fields from transformers, power lines, etc.

(d) Vacuum tubes with AC filament voltages are particularly prone to inducing hum into amplifier circuits.

In troubleshooting excessive hum in an amplifier, the four possibilities named above are examined one at a time, usually in the order given.

MATERIALS

1 NPN transistor type 2N1304 or equivalent
1 PNP transistor type 2N1305 or equivalent
2 Power transistors type TI3027 or equivalent
2 Transistor sockets
2 Breadboards
1 Output transformer (100Ω CT - 16/8/4Ω 5W)
1 Interstage transformer (500Ω CT - 200Ω CT 1/2W)
1 4-ohm resistor 2W
2 0.47-ohm resistor 2W
1 470-ohm resistor 1/2W
2 1k resistors 1/2W
1 1.8k resistor 1/2W
1 6.2k resistor 1/2W
1 6.8k resistor 1/2W
1 10k resistor 1/2W
2 15k resistor 1/2W
1 47k resistor 1/2W
4 10-μF 50W VDC capacitors
1 100-μF 50W VDC capacitor
1 Audio generator
1 Oscilloscope
1 VOM or FEM
1 .01 μF, 600W VDC capacitor

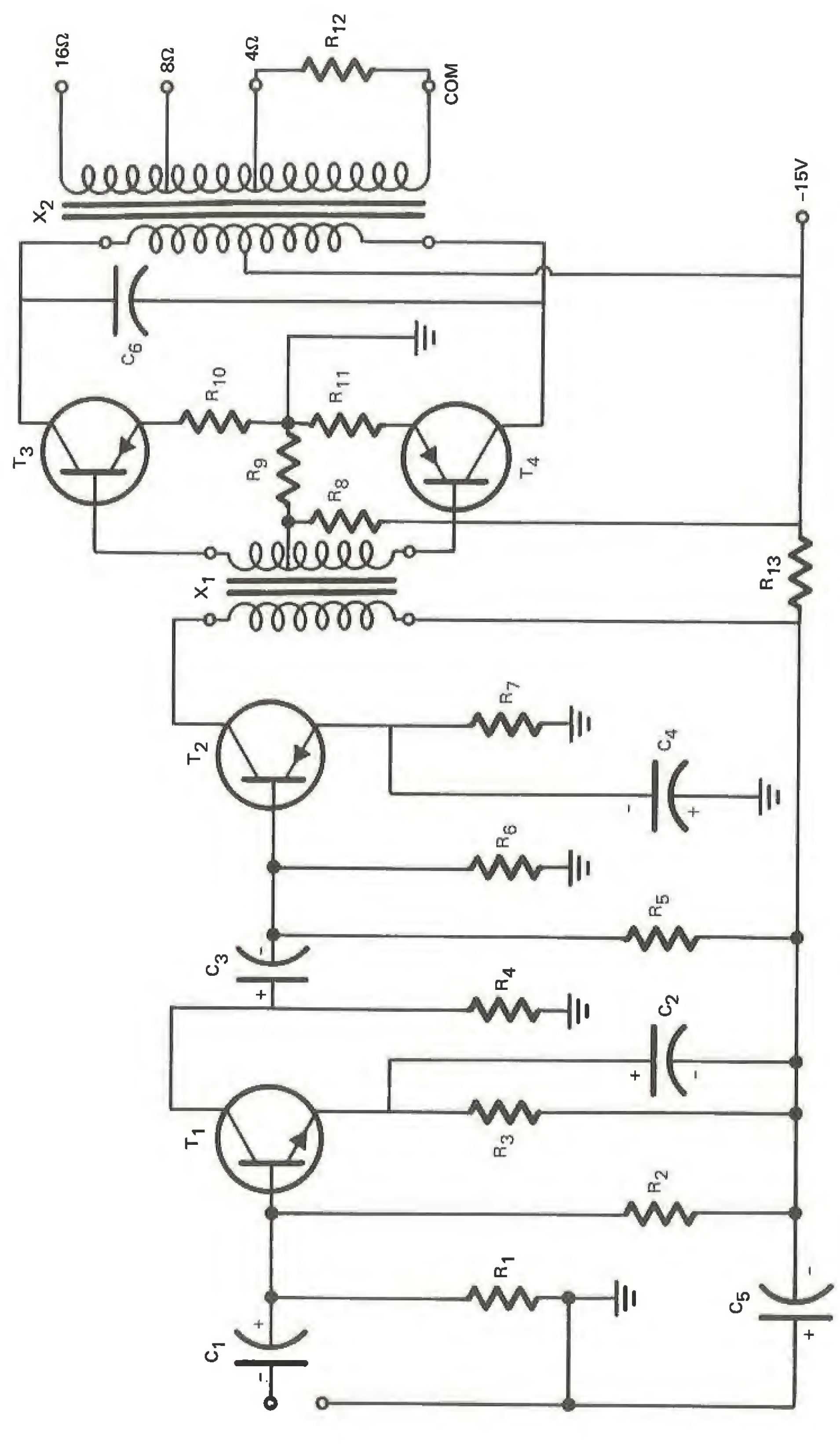
PROCEDURE

1. Assemble the circuit shown in figure 30-2. Construct the first two stages on one breadboard and the power amplifier on another. Keep your circuit wiring as neat and orderly as possible.

   T_1 = 2N1304 T_3 = TI3027
   T_2 = 2N1305 T_4 = TI3027

   See figure 30-2 for additional values

2. Check the amplifier for normal operation by noting the approximate values of V_{CE} for each transistor. Also note the approximate value of the overall voltage gain.
3. When you have the amplifier working normally, have the instructor "bug" (install a defect in) the circuit.
4. Using the techniques in the discussion, troubleshoot the problem. Enter the following information in the data table:
   (a) The nature of the problem: i.e., no output, hum, distortion, etc.
   (b) Circuit symptoms: i.e., high or low V_{CE} in one of the stages, no signal at some point, distortion at some point, etc.
   (c) Possible causes of the trouble. Using the circuit diagram, list the components which could cause the symptoms.
5. Using the information recorded above, locate the defect and correct it. Enter the cause of the defect in the data table.
6. Recheck the circuit for normal operation as in step 2.
7. Repeat steps 3 through 6 for as many defects as possible.



R_1 = 47k
R_2 = 6.2k
R_3 = 1.8k
R_4 = 6.8k
R_5 = 15k
R_6 = 10k
R_7 = 1k

R_8 = 15k
R_9 = 470Ω
R_{10} = 0.47Ω
R_{11} = 0.47Ω
R_{12} = 4Ω
R_{13} = 1k

C_1 = 10 μF 50V
C_2 = 10 μF 50V
C_3 = 10 μF 50V
C_4 = 10 μF 50V
C_5 = 100 μF 50V
C_6 = 0.01 μF 600V

X_1 = INPUT TRANS.
(500 CT TO 200 CT)

X_2 = OUTPUT TRANS.
(100 CT TO 16, 8, 4Ω)

Fig. 30-2 The Experimental Circuit

Nature of Problem	Circuit Symptoms	Possible Causes	Actual Cause

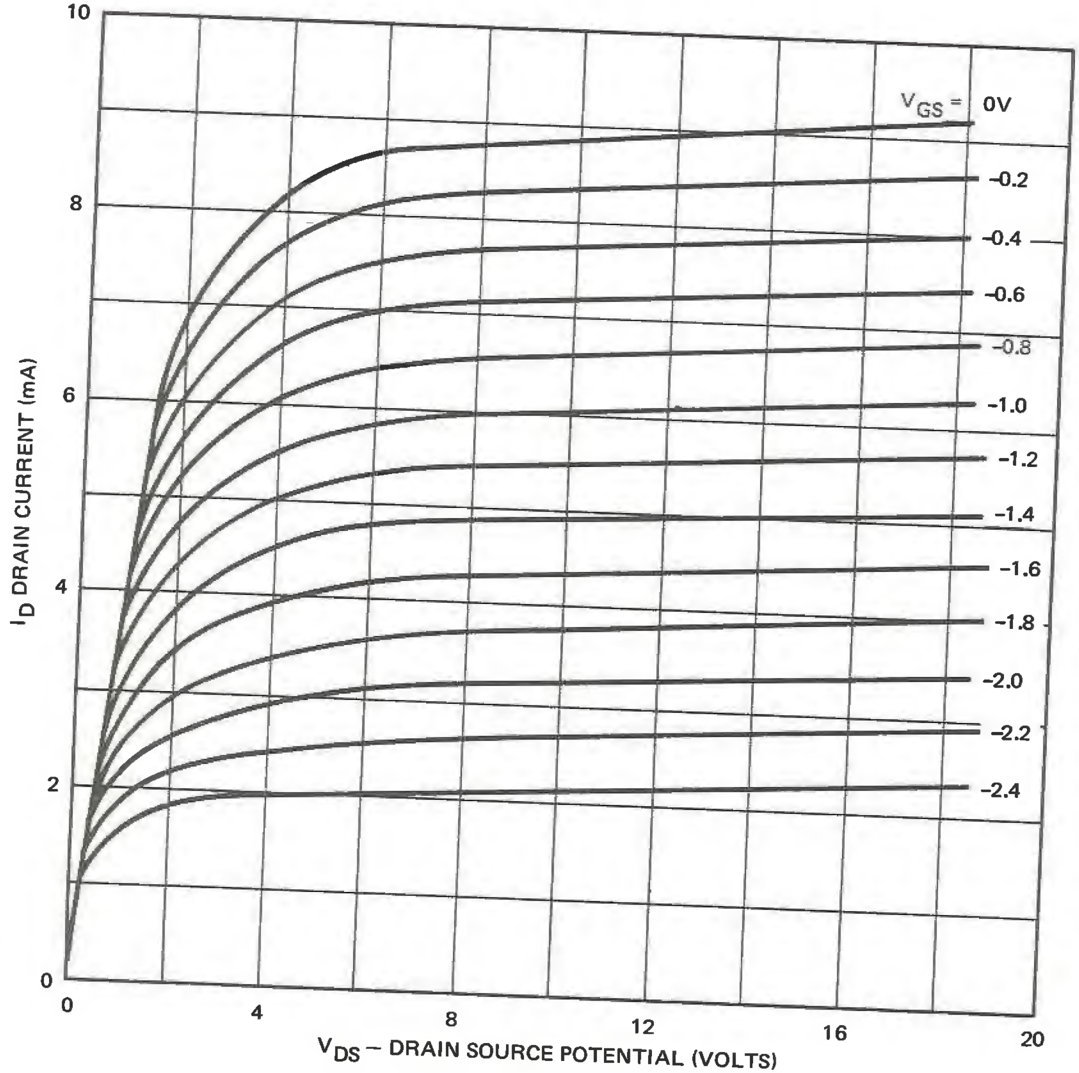
Fig. 30-3 The Data Table

ANALYSIS GUIDE. In analyzing the results of this experiment, you should discuss any difficulties you experienced in getting the circuit to work properly in the first place. Also explain *why* each of the defects encountered caused the symptoms that you observed.

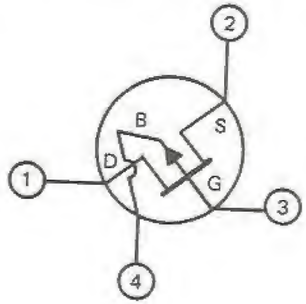
PROBLEMS. The following symptoms refer to the circuit shown in figure 30-1. In each case, list the components which could be defective and give the nature of the defect. For example: "second stage emitter resistor open-circuited."

1. Input signal normal, output dead, V_{CE} of first stage is 12 volts.
2. Output severely distorted, V_{CE} of T_3 is 10 volts, V_{CE} of T_4 is zero volts.
3. Severe hum in output (even if input is short-circuited), V_{CE} of all stages is slightly low.
4. Input signal to second stage normal at base of T_2, no output at T_2 collector. V_{CE} of T_2 is zero.

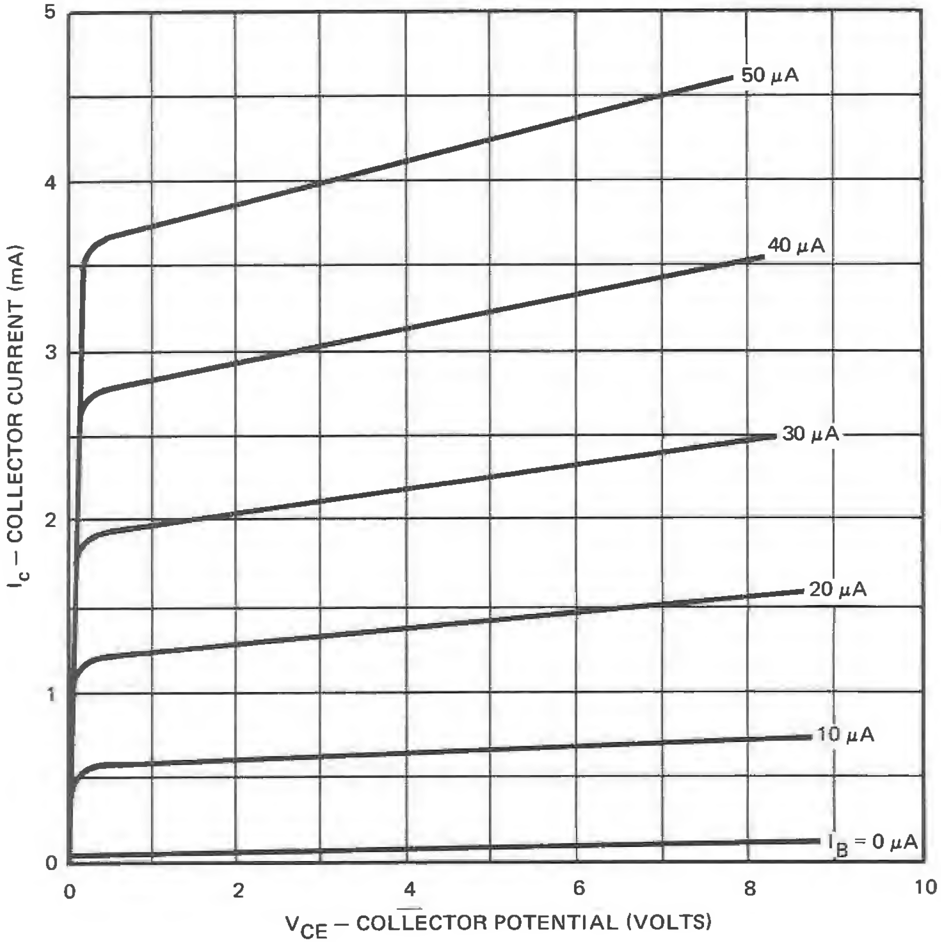
OUTPUT CHARACTERISTICS (Common Source)
MOSFET TYPE 40468



MAXIMUM RATINGS	
Drain-to-Source Volts	20 V
Gate-to-Source Volts	0 to –8 V
Peak Gate-to-Source Volts	±15 V
Drain Current	20 mA
Transistor Dissipation:	
T_A up to 85°C	100 mW
Temperature Range:	–65 to 100 °C
Leading-Soldering Temperature	265 °C
CHARACTERISTICS	
Gate-to-Source Cutoff Volts	–5 min: –8 max V
Gate Leakage Current	200 max pA
Forward Transadmittance	7.5 mmhos
Small-Sig. Reverse Trans Cap	0.1 to 0.2 pF
Small-Sig. Input/Output Cap.	5.5/1.4 pf
Input/output res.	4.5/4.2 k
Max. useable gain	14 db

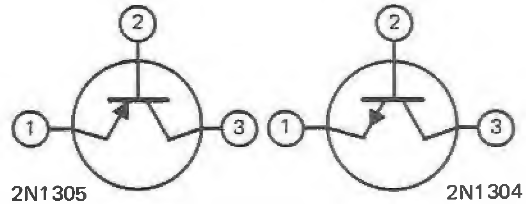


OUTPUT CHARACTERISTICS (Common Emitter)
for transistor types 2N1304 and 2N1305



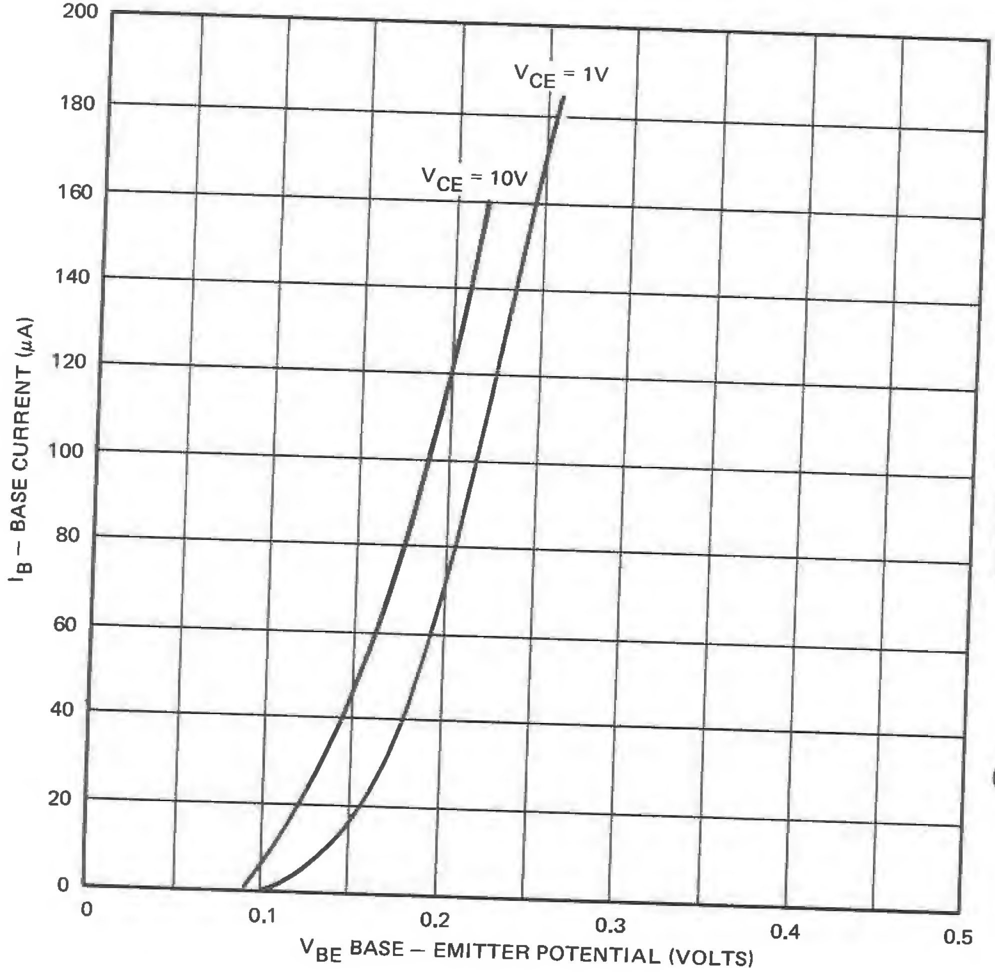
Characteristics	LIMITS Type 2N1304 Min.	Max.	Type 2N1305 Min.	Max.	Units
Collector-Cutoff Current	—	6	—	-6	μA
Emitter-Cutoff Current	—	6	—	-6	μA
Base-to-Emitter Voltage	0.15	0.35	-0.15	-0.35	volt
Collector-to-Emitter Saturation Voltage	—	0.2	—	-0.2	volt
DC Collector-to-Emitter Reach - Through Voltage*	20	—	-20	—	volts
DC Forward-Current Transfer Ratio	40 14	200 —	40 15	200 —	
Alpha-Cutoff Frequency	5	—	5	—	Mc
Collector-to-Base Capacitance	—	20	—	20	pf

TERMINAL DIAGRAMS
(Bottom View)



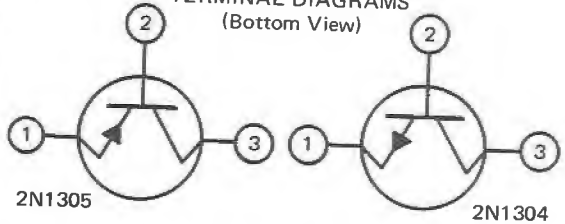
Lead 1 — Emitter
Lead 2 — Base, Case
Lead 3 — Collector

INPUT CHARACTERISTICS (Common Emitter) for transistor types 2N1304 and 2N1305



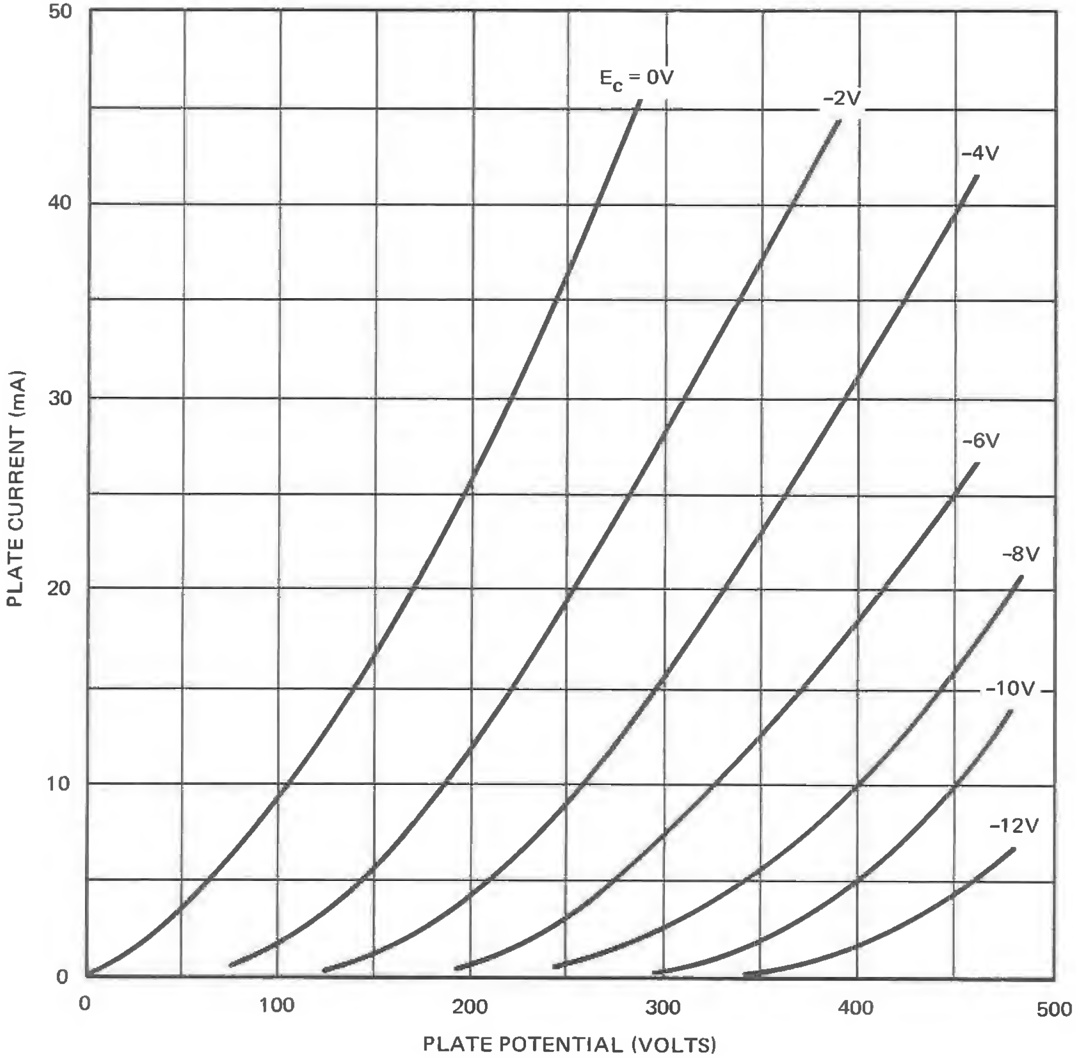
Characteristics	LIMITS Type 2N1304 Min.	Max.	Type 2N1305 Min.	Max.	Units
Col. – Cutoff I	—	6	—	-6	μA
Emitter – Cutoff I	—	6	—	-6	μA
Base-to-Emit. Volts	0.15	0.35	-0.15	-0.35	volt
Col.-to-Emit. Sat. Volts	—	0.2	—	-0.2	volt
DC Col.-to-Emit. Reach – Through Volts	20	—	-20	—	volts
DC Forward-Current Transfer Ratio	40 15	200 —	40 15	200 —	
Alpha-Cutoff Frequency	5	—	5	—	Mc
Col.-to-Base Capacitance	—	20	—	20	pf

TERMINAL DIAGRAMS
(Bottom View)

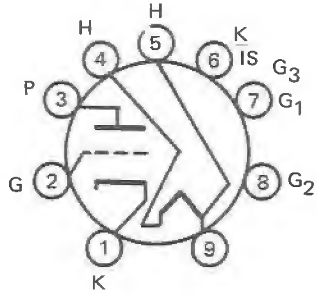


Lead 1 – Emitter
Lead 2 – Base, Case
Lead 3 – Collector

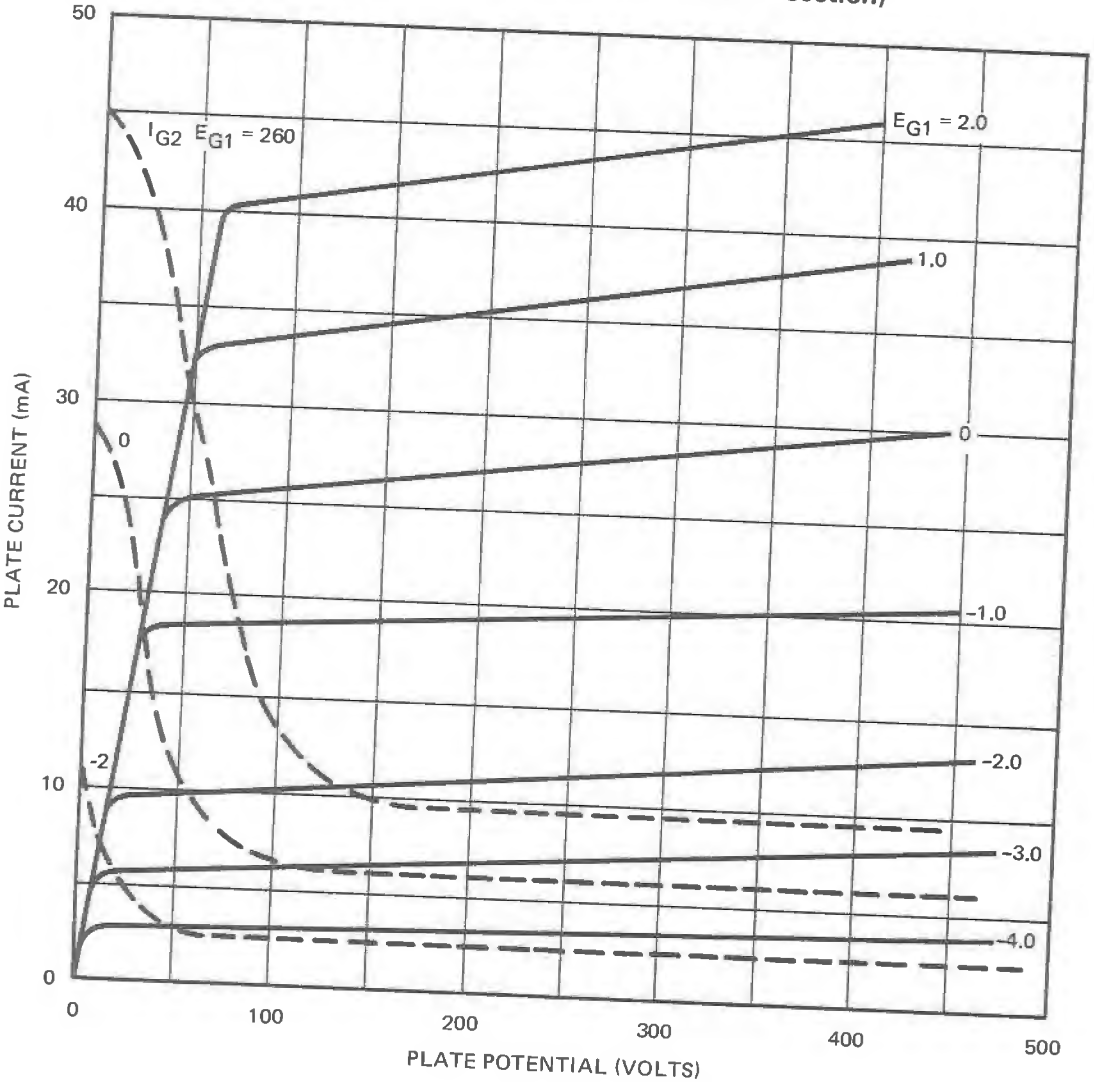
OUTPUT CHARACTERISTICS
Vacuum Tube Type 6AU8
(Triode Section)



Heater Voltage	6.3 V
Heater Current	600 mA
C_{gk}	2.6 pf
C_{pk}	0.34 pf
Plate dissipation	2.5 W
Amplification factor	40
Plate resistance	7200Ω
Transconductance	5600 umhos
Max grid circuit resistance	1.0 megohm
C_{gp}	2.2 pf

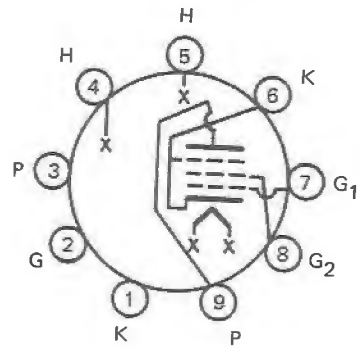


OUTPUT CHARACTERISTICS
Vacuum Tube Type 6AU8
(Pentode Section)

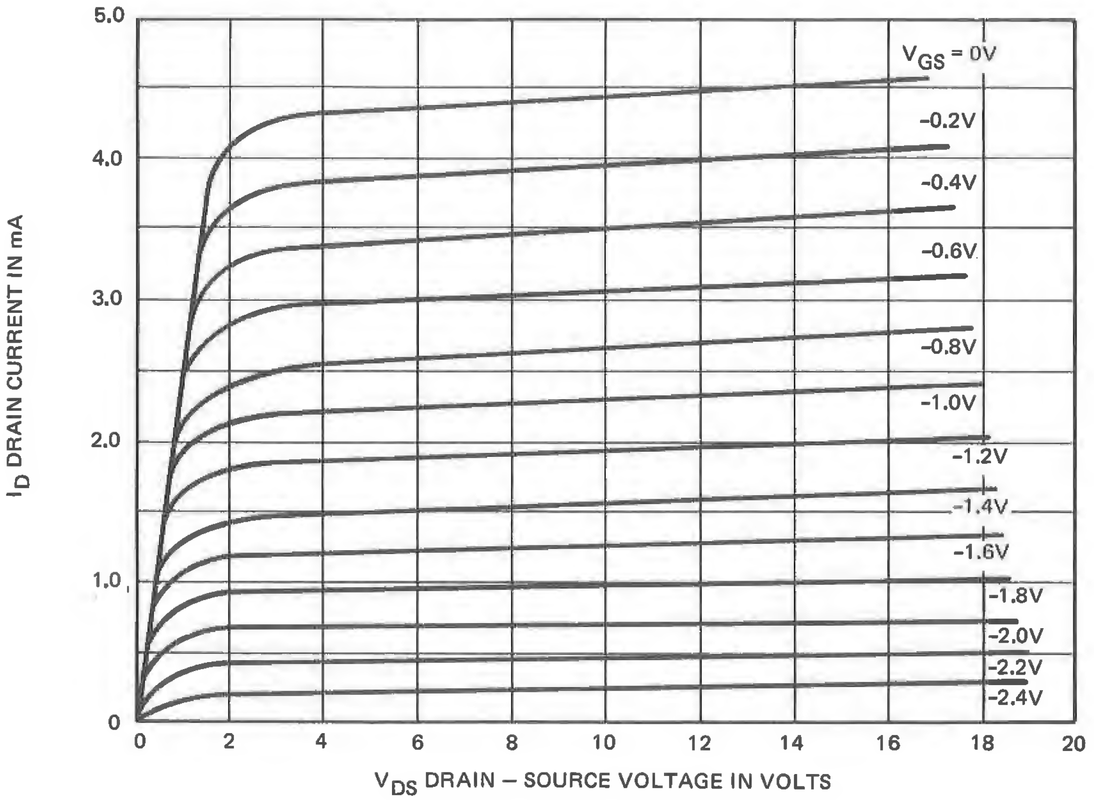


Heater Voltage	6.3 V
Heater Current	600 mA
C_{gk}	7.5 pf
C_{pk}	2.4 pf
C_{gp}	0.044 pf
Plate dissipation	3.0 W
Screen dissipation	1.0 W
Plate resistance	140 k ohms
Transconductance	8000 umhos
Max grid circuit R	1.0 megohm

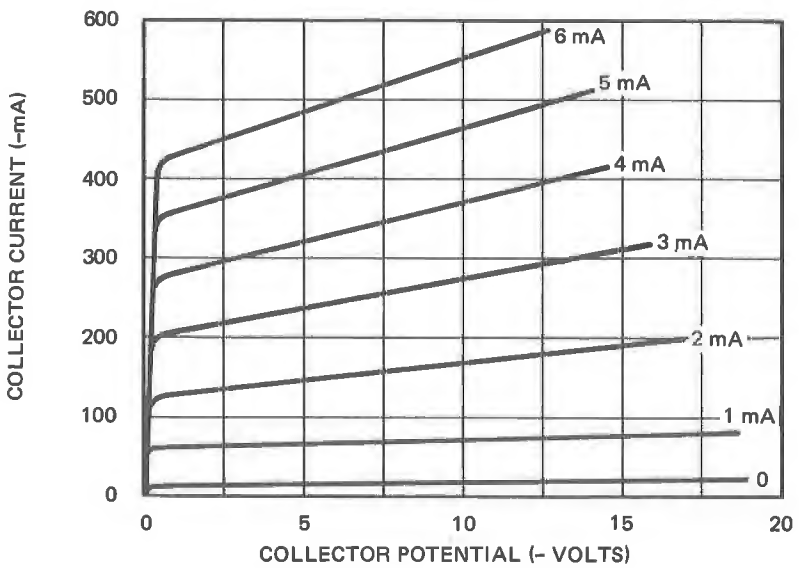
BOTTOM VIEW



Type 2N3819
Field Effect Transistor
N-Channel Planar Silicon



P-N-P ALLOY-JUNCTION
GERMANIUM POWER TRANSISTOR
TYPES TI3027, TI3028



TRANSFORMER DATA

TRANSISTOR OUTPUT TRANSFORMER
PRIMARY: 100 Ohms C.T. 500 mA DC Max. SECONDARY: 3.2 Ohms 8 Ohms 16 Ohms POWER LEVEL: 10 Watts

TRANSISTOR DRIVER TRANSFORMER
PRIMARY: 500 OHMS C.T. SECONDARY: 200 OHMS C.T. POWER LEVEL: 500 mW

EXPERIMENT 1 ____________ Name ____________

Date: ____________ Class ________ Instructor ________

Silicon Diode
Reverse Biased

E_R	E_D	I_D

Silicon Diode
Forward Biased

E_R	E_D	I_D

Fig. 1-10 The Data Tables

Zener Diode
Reverse Biased

E_R	E_D	I_D

Zener Diode
Forward Biased

E_R	E_D	I_D

Fig. 1-10 The Data Tables (Cont'd)

EXPERIMENT 1 ____________ Name ____________

Date: ____________ Class ____________ Instructor ____________

Vacuum Diode
Reverse Biased

E_R	E_p	I_p

Vacuum Diode
Forward Biased

E_R	E_p	I_p

Fig. 1-10 The Data Tables (Cont'd)

Silicon Diode Resistance

I_D (mA)	R_D	r_D
20		
40		
60		
80		
100		

Zener Diode Resistance

I_D (mA)	R_D	r_D
20		
40		
60		
80		
100		

Vacuum Diode Resistance

I_p (mA)	R_p	r_P
20		
40		

Fig. 1-10 The Data Tables (Cont'd)

EXPERIMENT 2 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

Circuit Values With No Filter					10 μF Filter	20 μF Filter	π Filter
E_m	R_L	E_{DC} Meas	I_{DC} Comp	E_{DC} Comp	E_{DC} Meas	E_{DC} Meas	E_{DC} Meas

Fig. 2-10 The Data Table

EXPERIMENT 3

Date: ______________________ Name ______________________

Class ____________ Instructor ______________________

Ckt.	E_m	E_{DC} (Comp)	I_{DC} (Comp)	E_{DC} (Meas)	I_{DC} (Meas)	E_{DC} (Filter)	I_{DC} (Filter)
First							
Second							

Fig. 3-13 The Data Table

EXPERIMENT 4

Date: ____________________ Name ____________________

Class ____________ Instructor ____________

TRANSISTOR DATA

I_B (μA)	0	20	40	60	80	100	120	140	160	180	200
V_{CE} (volts)	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C
0											
-1											
-2											
-4											
-6											
-8											
-10											
-12											
-14											
-16											
-18											
-20											

Fig. 4-9 The First Data Table

TRANSISTOR DATA

I_B (μA)	0	20	40	60	80	100	120	140	160	180	200
V_{CE} (volts)	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C	I_C
0											
–1											
-2											
-4											
-6											
-8											
–10											
–12											
–14											
–16											
–18											
-20											

Fig. 4-10 The Second Data Table

EXPERIMENT 5

Date: ____________________ Name ____________________

Class __________ Instructor __________

FET DATA

E_{GS} (volts)	-5.0	-4.5	-4.0	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	-0.0
E_{DS} (volts)	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D	I_D
0											
1											
2											
4											
6											
8											
10											
12											
14											
16											
18											
20											

Fig. 5-6 The Data Table

EXPERIMENT 6

Date: ______________ Name ______________ Class ______________ Instructor ______________

V_{CE} (volts)	1.0	5.0	10.0	12.5	20.0
I_B (μA)	V_{BE}	V_{BE}	V_{BE}	V_{BE}	V_{BE}
0					
20					
40					
60					
80					
100					
120					
140					
160					
180					
200					

Fig. 6-5 The Data Table

EXPERIMENT 7

Date: ____________

Name ____________

Class ________ Instructor ____________

Circuit Conditions			V_{CC} = 10V V_{BB} = 1.5V			R_L = 3.3k R_B = 47k		
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Circuit Conditions			V_{CC} = 12V V_{BB} = 2.0V			R_L = 4.7k R_B = 68k		
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Fig. 7-6 The Data Tables

Circuit Conditions			V_{CC} = 9V V_{BB} = 1V			R_L = 2.2k R_B = 33k		
Quantity	I_C	I_B	I_E	V_{CE}	V_{BE}	V_{CB}	E_L	E_B
Comp. Data								
Meas. Data								
% Diff.								

Fig. 7-6 The Data Tables (Cont'd)

EXPERIMENT 8

Date: ____________ Name ____________

Class ____________ Instructor ____________

R_E (ohms)	I_B (μA)	I_C (mA)	α_F	I'_C (mA)	ΔI_C (mA)	S
0						
470						
1000						
1500						
2200						
3300						
4700						

Data from First Experimental Circuit

Fig. 8-9 The Data Tables

Bias Circuit	I_B (μA)	I_C (mA)	V_{BB} (volts)	R_B (ohms)	ΔI_C (mA)
R_1, R_2 Network					
V_{BB}, R_B Network					

Data from Second Experimental Circuit

Fig. 8-9 The Data Tables (Cont'd)

EXPERIMENT 9

Date: ______________ Name ______________

Class ________ Instructor ______________

Qty.	V_{CE}	I_C	I_B	V_{BE}	r_i	Z_i	i_B	Ie_c	i_s	i_c	e_s	e_o	A_v	i_L	A_i	A_p
Loadline Values																
Measured Values																

Fig. 9-9 The Data Table

EXPERIMENT 10 ______________ Name ______________________

Date: ______________________ Class __________ Instructor ______________

E_{GK} (volts)	-14	-12	-10	-8	-6	-4	-2	0	+2
E_{PK} (volts)	I_P	I_P	I_P	I_P	I_P	I_P	I_P	I_P	I_P
0									
50									
100									
150									
200									
250									
300									
350									
400									

E_{GK} (volts)	-5	-4	-3	-2	-1	0
E_{PK} (volts)	I_P	I_P	I_P	I_P	I_P	I_P
0						
50						
100						
150						
200						
250						
300						
350						
400						

Fig. 10-9 The Data Tables

EXPERIMENT 11

Date: ____________________ Name ____________________

Class __________ Instructor ____________________

Quantity	E_P	I_P	E_G
Loadline Data			
Measured Data			

Triode Cathode Bias Data

Quantity	E_P	I_P	E_G	I_G
Loadline Data	X	X		X
Measured Data				

Triode Grid Leak Bias Data

Quantity	E_{G2}	I_{G2}	E_P	I_P	E_{G1}
Loadline Data					
Measured Data					

Pentode Data

Fig. 11-11 The Data Tables

EXPERIMENT 12

Date: ____________ Name ____________ Class ________ Instructor ____________

Qty.	E_{PK}	I_P	E_G	R'_L	$\frac{e_o}{(P-P)}$	A_v	Power Sens.
Graphical Values							
Measured Values							

Fig. 12-7(a) Triode Amplifier Data

Qty.	E_{PK}	I_P	E_G	R'_L	$\frac{e_o}{(P-P)}$	A_v	Power Sens.
Graphical Values							
Measured Values							

Fig. 12-7(b) Pentode Amplifier Data

EXPERIMENT 13

Date: ____________ Name ____________

Class ________ Instructor ____________

V_{DS} (Volts)	I_D (mA)	V_{GS} (Volts)	X_C @ 1 kHz (ohms)

Resistance Box Value	2.2k	4.7k	10k	22k	47k
R_L =					
A_v =					
Power sens =					

(A) COMPUTED DATA

Resistance Box Setting	2.2k	4.7k	10k	22k	47k
V_{DS} (volts)					
I_D (mA)					
V_{GS} (volts)					
e_s (volts p-p)					
e_o (volts p-p)					
A_v					
Power sens.					

(B) MEASURED DATA

Fig. 13-6 The Data Table

EXPERIMENT 14

Date: ____________________

Name ____________________

Class __________ Instructor ____________________

	h_{fe}	r_D	g_m
Values from Characteristic curves			

Transistor Data	
∂i_B	
e_{AC}	
∂i_C	
h_{fe}	

FET Data	
∂V_{DS}	
∂i_D	
r_D	
∂V_{GS}	
e_{AC}	
g_m	

Fig. 14-15 The Data Table

EXPERIMENT 15

Date: ______________________ Name ______________________

Class ____________ Instructor ______________

Qty	V_{CE}	I_C	I_B	h_{ie}	h_{fe}	h_{re}	h_{oe}	K_v	K_i	K_p	R_{in}	R_o
Computed Values												
Measured Values												

Fig. 15-12 The Data Table

EXPERIMENT 16 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

Quantity	E_C	E_P	I_P	μ	g_m	r_P
Computed Values						
Measured Values						

Quantity	K_v	K_i	K_P	R_{in}	R_o
Computed Values					
Measured Values					

Fig. 16-8 The Data Table

EXPERIMENT 17 ____________ Name ____________________

Date: ____________________ Class ____________ Instructor ____________

QTY	V_{DS}	V_{GS}	I_D	μ	g_m	r_D	K_v	K_i	K_P	R_{in}	R_o
Computed Values											
Measured Values				X	X	X					

Fig. 17-8 The Data Table

EXPERIMENT 18 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

Quiescent Conditions

QTY	FET Circuit		Transistor Circuit	
	V_{DS}	V_{GS}	V_{CE}	V_{BE}
Computed Value				
Measured Value				

First Test Circuit

Capacitor																				
K_i																				

Second Test Circuit

Capacitor																				
K_i																				

Fig. 18-7 The Data Tables

EXPERIMENT 19 ____________ Name ____________________

Date: ____________________ Class __________ Instructor ____________

Output Stage Data			
e_o	e_2	K_{v3}	A_{v3}

Input Stage Data				
e_g	e_s	e_1	K_{v1}	A_{v1}

Coupling Circuit Data			
e_1	e_2	K_{v2}	A_{v2}

Overall Gain Values			
K_{vT}	Av_T	A'_{vT}	K'_{vT}

Fig. 19-6 The Data Tables

EXPERIMENT 20 ______________ Name ______________

Date: ______________ Class ________ Instructor ________

f (Hz)	No Cap. e_o (volts)	No Cap. A_v (db)	Series Cap. e_o (volts)	Series Cap. A_v (db)	Both Cap. e_o (volts)	Both Cap. A_v (db)
100						
200						
300						
400						
500						
600						
700						
800						
900						
1k						
2k						
3k						
4k						
5k						
6k						
7k						
8k						
9k						
10k						
20k						
30k						
40k						
50k						
60k						
70k						
80k						
90k						

e_{in}	
f_1 Comp.	
f_1 Curve	
f_2 Comp.	
f_2 Curve	

Fig. 20-6 The Data Tables

EXPERIMENT 21 ____________ Name ____________________

Date: ____________________ Class ____________ Instructor ____________

Qty	e_o	e_1	e_2	e_d	e_c	A_c	A_d	ρ
First Ckt								
Second Ckt								

Fig. 21-7 The Data Table

EXPERIMENT 22 ______________ Name ______________________

Date: ______________________ Class __________ Instructor ______________

QTY	e_s	A_m	f_2	e_x	R_i	R_o	β	e_o
Open Loop Values							X	
Feedback Values							X	
Computed Values	X			X				X

Fig. 22-5 The Data Table

EXPERIMENT 23 ______ Name ______

Date: ______ Class ______ Instructor ______

QTY	A_v Meas.	R_i	R_o	β	A′ Comp
Circuit With Emitter Bypassed					
Circuit With Emitter Unbypassed					
Emitter Follower					

Fig. 23-7 The Data Table

EXPERIMENT 24 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

First Circuit

R_f Ohms	A' Comp	A' Meas
470		
1k		
2.2k		
4.7k		
10k		
33k		
68k		
100k		
220k		
470k		

Second Circuit

e_o Comp	e_o Meas

Fig. 24-11 The Data Tables

EXPERIMENT 25 ____________ Name ____________

Date: ____________ Class ____________ Instructor ____________

R (ohms)	1 meg	680 K	470 K	330 K	220 K	100 K
E_o (volts)	T (Sec)	T (Sec)	T (Sec)	T (Sec)	T (Sec)	T (Sec)
0.5						
1.0						
1.5						
2.0						
2.5						
3.0						
3.5						
4.0						
4.5						
5.0						
5.5						
6.0						
6.5						
7.0						
7.5						
8.0						
8.5						

Fig. 25-10 The Data Table

EXPERIMENT 26 ______ Name ______

Date: ______ Class ______ Instructor ______

Input DC Voltage	Output Signal (Show Amplitude and Phase)
0	+ 0 –
5	+ 0 –
10	+ 0 –
15	+ 0 –
20	+ 0 –
0	+ 0 –
-5	+ 0 –
-10	+ 0 –
-15	+ 0 –
-20	+ 0 –

Fig. 26-5
The Data Table

EXPERIMENT 27 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

E_A	E_B	E_O	E_C	E_E	E_F	E_G	E_H	E_i

Fig. 27-14 The Data Table

EXPERIMENT 28 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

Qty	R_C	N_p/N_s	E_Q	I_Q	E_o (rms)	E_{in} (rms)	R_{in}	P_o	P_{in}	K_P (db)
Measured Values										
Computed Values	X	X			X	X	X		X	X

Fig. 28-5 The Data Table

EXPERIMENT 29 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

Qty	R_C	$\frac{N_p}{N_s}$	I_C	V_{CE}	R_p	I_{max}	P_o comp.	e_o	P_o meas.	P_i meas.	K_p
Value											

Fig. 29-6 The Data Table

EXPERIMENT 30 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

Nature of Problem	Circuit Symptoms	Possible Causes	Actual Cause

Fig. 30-3 The Data Table